Interim Report

for

Monitoring and Evaluation of Thin Bonded Overlays and Surface Laminates for Bridge Decks

Prepared for the

Montana Department of Transportation
Research, Development, & Technology Transfer Program

in cooperation with the

U.S. Department of Transportation
Federal Highway Administration
Demonstration Projects Program

by

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16. Abstract
This study, part of a larger national effort to research thin bonded overlays for bridge decks, investigated the relative performance and costs of various technologies used for thin overlays on concrete bridge decks. This element of the program considered four different overlay treatments applied to a total of 13 bridges along Interstate 90 in southwestern Montana. The overlay technologies considered consisted of two Portland cement related products, an acrylic polymer modified, cement-based topping (Thorotop HCR) and silica fume concrete; and two resin/aggregate systems, one with an epoxy binder (Flexolith 216) and one with a methyl methacrylate (MMA) binder (Degadur 330BD). Extensive documentation was collected on the pre-overlay condition of the decks, the overlay installation processes, the initial condition of the overlays, and the condition of the overlays after one or two winter(s) of service. The Flexolith 216 and Degadur overlays exhibit limited cracking, but no significant delaminations or dramatic loss of surface roughness, after two years of service. The Thorotop HCR overlays have worn off in heavily trafficked areas of the decks on one set of bridges. Concerns have also developed regarding the skid resistance of the Thorotop overlays. The silica fume concrete overlay, in service for only one year, exhibits few signs of distress. Regarding costs, bid prices for the Thorotop HCR, silica fume, Flexolith 216, and Degadur overlays were $22, $40, $36, and $44 per square yard of surface area, respectively. Comparing life cycle costs of these various deck treatments, however, is difficult, in that not enough time has gone by in most cases for clear differences to emerge in the long term performance between overlay treatments.

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Abstract

This study, part of a larger national effort to research thin bonded overlays for bridge decks, investigated the relative performance and costs of various technologies used for thin overlays on concrete bridge decks. This element of the program considered four different overlay treatments applied to a total of 13 bridges along Interstate 90 in southwestern Montana. The overlay technologies considered consisted of two Portland cement related products, an acrylic polymer modified, cement-based topping (Thorotop HCR) and silica fume concrete; and two resin/aggregate systems, one with an epoxy binder (Flexolith 216) and one with a methyl methacrylate (MMA) binder (Degadur 330BD). Extensive documentation was collected on the pre-overlay condition of the decks, the overlay installation processes, the initial condition of the overlays, and the condition of the overlays after one or two winter(s) of service. The Flexolith 216 and Degadur overlays exhibit limited cracking, but no significant delaminations or dramatic loss of surface roughness, after two years of service. The Thorotop HCR overlays have worn off in heavily trafficked areas of the decks on one set of bridges. Concerns have also developed regarding the skid resistance of the Thorotop overlays. The silica fume concrete overlay, in service for only one year, exhibits few signs of distress. Regarding costs, bid prices for the Thorotop HCR, silica fume, Flexolith 216, and Degadur overlays were \$22, \$40, \$36, and \$44 per square yard of surface area, respectively. Comparing life cycle costs of these various deck treatments, however, is difficult, in that not enough time has gone by in most cases for clear differences to emerge in the long term performance between overlay treatments.

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English to Metric Conversion Table

English	**Metric**
Length	
1 mil	0.0254 mm
1 inch	2.540 cm
1 foot	30.480 cm
1 yard	0.914 m
1 mile	1.609 km
Area	
1 $ft.^2$	0.0929 m^2
1 $yd.^2$	0.836 m^2
Volume	
1 $yd.^3$	764.555 l
Weight	
1 pound	0.454 kg
Pressure	
1 psi	6.895 kPa
Temperature	
1°F	0.556 C

1. INTRODUCTION

1.0 GENERAL REMARKS

The objective of this program is to evaluate the relative performance and costs of various technologies used for thin overlays on concrete bridge decks. The original program considered three deck treatments which had not previously been tried within the State of Montana, namely: an acrylic polymer modified cement-based deck topping (Thorotop HCR), an epoxy/aggregate system (Flexolith 216), and a silica fume concrete. A fourth treatment, a methyl methacrylate (MMA) resin and aggregate system (Degadur 330BD) which has previously been used by the Montana Department of Transportation (MDT), was also included in the program. These treatments were placed on a total of 12 bridge decks at 6 locations along Interstate 90 in southwestern Montana (pairs of east and westbound bridges were overlaid at each location). An additional MMA deck was added to the program on a newly constructed bridge on an arterial crossing Interstate 90. Installation and evaluation of these overlays were partially funded through, and were part of, a national program entitled: Applied Research and Technology Program: Thin Bonded Overlay and Surface Lamination (TBO), which was authorized under ISTEA Section 6005. The actual overlay work was contracted by MDT during the 1995 and 1996 construction seasons. All overlays except the MMA treatment on the arterial were contracted as Federal Aid Project No. IM 0002(50) - Statewide Interstate Bridge Deck Improvement.

To evaluate the relative performance and life cycle costs of the various deck treatments fully and fairly, extensive data were (and are being) collected on the properties of the materials used in each overlay, the details and cost of their installation, and their subsequent in-service performance. The program plan (*1*) enumerated seven tasks to be performed for this evaluation process:

1. Evaluate the conditions at each installation site before the overlay is placed.
2. Document the specifications for each installation.
3. Record results of job control testing or quality assurance for each site.
4. Evaluate initial conditions after placement of each installation.
5. Evaluate condition of each installation annually.
6. Evaluate condition of each installation at the end of the program.
7. Analyze the data collected above and generate a report that documents the work performed, the estimated service life of each overlay, and an assessment of the cost effectiveness of each overlay.

This evaluation program was developed by the Federal Highway Administration for the national thin bonded overlay project and is presented in detail in "Thin Bonded Overlay and Surface Laminates Bridge Deck Overlay Evaluation Plan" (*2*). MDT contracted with the Civil Engineering Department at Montana State University (MSU) to perform most of the data gathering activities in Tasks 1 through 6 and to perform the analyses and generate life cycle costs for Task 7. Another portion of the documentation for this program included the production of a video on the installation of each technology that shows conditions before, during, and after construction. MSU assumed responsibility for this video.

Tasks 1 through 6 have been completed for each overlay installation, and the resulting data are presented in this report. While some information has been assembled on cost and performance, insufficient time has gone by (approximately 2 years on the Thorotop HCR, Flexolith 216, and Degadur 330BD decks, and 1 year on the silica fume decks) to comprehensively compare expected life cycle costs among all technologies. Only in certain cases have sufficiently obvious trends in overlay performance emerged to permit definitive conclusions on relative overlay performance. In most cases, reliable and comprehensive indications of long term overlay performance can only be obtained by extending the monitoring program. Note that this program was originally envisioned with a minimum of a 5-year evaluation period.

2. OVERLAY TECHNOLOGIES AND INSTALLATION SITES

2.0 GENERAL REMARKS

The overlay technologies considered in this project and the sites at which they have been installed are summarized in Table 2.0.1. Four overlay technologies were considered, namely Thorotop HCR, silica fume, Flexolith 216, and Degadur 330BD. These overlay treatments represent two broad approaches to thin bonded overlays for concrete bridge decks. Thorotop HCR and silica fume are cement-based products and thus involve the hydration of a cement/admixture paste mixed with fine aggregate or filler to form a mortar-like overlay material. Flexolith 216 is an epoxy and Degadur MMA is an plastic resin material, and thus these treatments involve mixing two components together which subsequently chemically react to form a hard, plastic-acrylic material in which fine aggregate is incorporated. Various aspects of the materials and installation processes associated with each overlay treatment are described in detail in the Special Provisions for Federal Aid Project No. IM 0002(50) (*3*). Additional information on the treatments is available from the manufacturers. A brief overview of each overlay treatment, assembled from these sources of information, is presented in this section of this report. Specific information on the manner in which these overlays were installed in this demonstration project is presented in Section 3 of this report.

The overlay treatments were applied to 13 bridges along Interstate 90 in southwestern Montana at the locations shown in Figure 2.0.1. With the exception of the Degadur MMA installation near Milepost 305 on the 19th Street Interchange west of Bozeman, the overlaid bridges carry the traffic on Interstate 90. At each of these installations, the bridge decks in both directions of travel (in this case, eastbound and westbound) were overlaid. The 19th Street bridge carries local traffic over Interstate 90. The Gallatin River and West Garrison Interchange bridges were overlaid with Thorotop HCR polymer overlay. The Madison River and East Garrison Interchange bridges were overlaid with Flexolith 216 epoxy overlay. The Galen Interchange received a silica fume concrete overlay. Degadur MMA was applied to the bridges over an abandoned railroad right-of-way near the Fairmont exit of Interstate 90 and at the 19th Street bridge near Bozeman.

Table 2.0.1: Summary of Overlaid Decks.

Location (along I-90)	**Date Overlaid**	**Feature Crossed**	**Overlay Treatment**
MP 304+0.694	6/95	Interstate 90	Degadur MMA
MP 292+0.425	8/8 - 8/15/95	Gallatin River	Thorotop HCR
MP 278+0.857	8/23 - 9/1/95	Madison River	Flexolith 216
MP 210+0.803	9/26 - 10/2/95	Abandoned R. R./Fairmont	Degadur MMA
MP 197+0.560	7/15 - 7/29/96	Galen Interchange	Silica Fume
MP 175+0.533	9/6 - 9/14/95	E. Garrison Interchange	Flexolith 216
MP 174+0.323	9/18 - 10/11/95	W. Garrison Interchange	Thorotop HCR

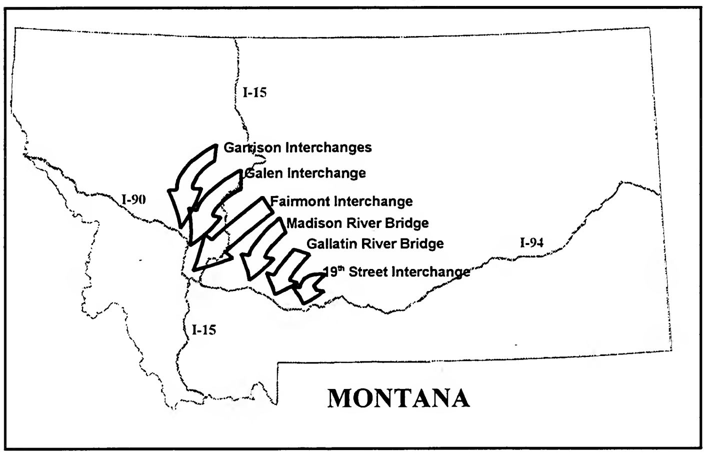


Figure 2.0.1: Location of Demonstration Projects.

2.1 OVERLAY TECHNOLOGIES

2.1.1 Thorotop HCR

The technology used on the Gallatin and West Garrison Interchange Bridges was Harris Specialty Company's (Miami, FL) Thorotop HCR (*4*). Thorotop HCR (horizontal concrete resurfacer) is an acrylic polymer modified, cement-based material. This material has historically been used on parking structures (according to the manufacturer's representatives). Basic properties

of the overlay material, itself, as stated by the manufacturer are presented in Table 2.1.1. Mixture proportions for Thorotop HCR are five quarts of Thoro polymer additive (acrylic resin) per fifty pounds Thoro HCR powder (cement base). Thorotop is placed in two lifts. The first lift is approximately 1/8-inch thick. The second and final lift is approximately 1/16-inch thick. Thus, the total thickness is 3/16-inch. No design life for this product is available from the manufacturer.

Table 2.1.1: Specifications for Thorotop HCR (adapted from (*4*))

Item:	**Specification:**
Pot Life (Test method not specified)	1 hour
Tensile Strength (ASTM C190)	1050 psi. (28 days)
Curing Shrinkage (ASTM C596)	-0.10% (28 days @ 70°F and 50% relative Humidity)
Min. Compressive Strength (ASTM C109)	2450 psi. (2 hrs.)
Min. Compressive Strength (ASTM C109)	4583 psi. (24 hrs.)
Min. Adhesion Strength (Test method not specified)	325 psi. (28 days)

The recommended installation procedure for Thorotop HCR, as given by the manufacturer, involves preparing the deck to provide a clean rough surface. Any areas requiring patching are to be filled with concrete and allowed adequate curing before overlaying with Thorotop. Adequate curing, as defined by Harris Specialty, is the accumulation of 5,000 degree-hours of curing (i.e.: 50 degree-hours is equal to one hour at 50°F, thus at an average temperature of 50°F, approximately 4.2 days would be required to obtain adequate cure). The initial lift of Thorotop is placed on a moistened surface. The second lift is applied 45 minutes to one hour after the first lift. Once the second lift achieves an initial set, a tined or stiff broom finish is applied perpendicular to traffic. No special measures are required during the curing of this product. The surface can be opened to traffic after 5,000 degree-hours of curing have occurred.

2.1.2 Silica Fume Concrete

Silica fume modified concrete was used on the Galen Interchange bridge. Silica fume, a pozzolanic by-product of ferrosilicon and silicon metal production, is used as an admixture in concrete generally to increase its strength and reduce its permeability. Of the treatments considered in this study, this product most resembles a traditional concrete. With a design thickness of 1.5 inches, the silica fume concrete is the thickest of all of the investigated overlay materials. No design life is available for this overlay treatment.

The mix design for the silica fume concrete used in this project, as given in the contract specifications (*3*), is presented in Table 2.1.2. This mix includes cement, water, aggregate, air, silica fume, and various other admixtures. With the exception of its gradation, the aggregate used in the concrete must meet state standards for concrete aggregate (*5*). The required aggregate consists of a course fraction (predominately #4 in size), and a fine fraction (primarily #16 to #50 in size). Specific gradation is given in the contract documents (*3*).

Preparation of a deck for a silica fume overlay, as indicated in the Special Provisions for this contract (*3*), consists of milling and scarifying the surface to a depth of 0.25 inches. Repairs are made with a concrete mixture with a rough finish. Application of the overlay is made in a single continuous lift. Brushing with burlap followed by tining perpendicular to traffic provides a highly skid resistant finish. Curing is done with an impervious membrane in accordance with standard state specifications for impervious curing membranes (*5*). Traffic reintroduction is allowed after a minimum of 4 days of curing and after the concrete displays minimum compressive strengths of 5,000 psi.

Silica fume products have a number of constraints on their placement imposed by MDT (*3*). Placement can only occur between May 15 and September 15, inclusive. Temperatures have to be at least 45°F for a minimum of six hours after placement. Maximum allowable ambient placement temperature is 80°F. A critical evaporation rate of 0.15 lbs./sq. ft./hr cannot be exceeded during placement or during the curing period. This rate is influenced by wind speed, air temperature, and relative humidity, as discussed in the contract documents (*3*).

Table 2.1.2: Silica Fume Mix Design (adapted from (*3*))

Item	**Quantity/Value**
Type I-II SR (10-50)	1.0 (parts by weight)
Fine Aggregate	1.8 (parts by weight)
Coarse Aggregate	2.5 (parts by weight)
Silica Fume	Minimum of 7.5 lbs./Sack Cement
High Range Water Reducer	As Per Manufacturer's Recommendations
Air	4-7 Percent of Plastic Mix
Water	0.40 Water: to Cement Ratio
Mix Temperature	50°F-85°F
28-Day Compressive Strength	>7500 psi
Slump	4-8 Inches

2.1.3 Flexolith 216 Epoxy

Flexolith 216, from Tamms Industries/Dural International Corporation, (Kirkland, IL) (*6*), was the technology selected for the Madison River and East Garrison Interchange bridges. A summary of Flexolith 216 specifications is given in Table 2.1.3. Flexolith 216 is a 2-part epoxy with an aggregate component. No design life is available for this product. According to the manufacturer's literature, however, earlier versions of Flexolith have been installed in similar cold weather applications for the past thirty years. Surface preparation is such that a clean rough surface free of physical defects is produced. Repairs are generally done with Flexolith 216 (which was the repair method used on this project). Large areas can be patched using a cementitious material compatible with Flexolith.

The aggregate used with Flexolith 216 is a crushed basalt sieved and segregated from sizes #6 to #20 (*6*). The aggregate is either mixed into the epoxy (slurry method of application), or spread on the surface before the epoxy has reached its initial set (broom and seed method of application). This contract (*3*) specified use of the broom and seed method. Following this procedure, the base resin and the hardener are mixed in equal proportions for three minutes. The mixture is spread with squeegees to a uniform depth on the dry prepared surface. Aggregate is broadcast by hand onto the

wet surface so that the surface is covered, as judged by the elimination of all wet spots. After the mixture has reached its initial cure (approximately 5 hours at 75°F), the excess aggregate is removed by sweeping the surface. Two equally thick lifts are utilized to achieve a minimum total thickness of 3/8-inch. Application of a seal coat is optional. Traffic reintroduction is allowed after 24 hours.

Table 2.1.3: Specifications for Flexolith 216 (adapted from (*6*))

Item:	**Specification:**
Pot Life (ASTM C881)	< 30 Minutes at 50°F
Tensile Strength (ASTM D638)	2700 psi. (28 days)
Tensile Elongation (ASTM D638)	45% of Minimum
Curing Shrinkage (ASTM C883)	Passes
Brookfield Viscosity	1700 cps at 75°F
Min. Compressive Strength (ASTM C109)	7000 psi.
ACI 503R-30 Adhesion	Concrete Failure

2.1.4 Degadur 330BD MMA

Degadur 330BD MMA, produced by Degussa Corporation (Ridgefield Park, NJ) (*7*), was used on the bridge deck near the Fairmont Interchange at Milepost 210 and on the 19th Street Interchange bridge. MMA products have previously been used by MDT for thin bonded bridge overlays. Note that MMA systems available from Silikal Resin Systems (Trabuco Canyon, CA) and Stockhausen (Greensboro, NC) were also listed as acceptable MMA treatment alternatives by the contract documents (*3*). MMA is a methacrylate resin that hardens rapidly in the presence of a hardening powder. The Degussa 330BD system, similar to the Flexolith 216 system, consists of an abrasive aggregate surface anchored by a resin layer to the surface of the bridge deck. Table 2.1.4. summarizes the specifications for Degadur 330BD as provided by the manufacturer. No design life is available for this product.

Table 2.1.4: Specifications for Degadur 330BD (adapted from (*7*))

Item:	Specification:
Pot Life	20-25 minutes
Compressive Strength (ASTM D695)	2500-3000 psi
Tensile Strength (ASTM D638)	500-700 psi
Flexural Strength (ASTM C580)	1300-1500 psi
Bond Strength (ACI 503R)	>250 psi
Coefficient of Thermal Expansion (VDE 0304/1)	$4.4\text{X}10^{-5}$ in/in/°F
Freeze/Thaw (ASTM C666)	Passed

Deck preparation for Degadur 330 BD consists of cleaning the surface with either a shotblaster or a sandblaster and repairing the deck, as required, with an appropriate concrete ("BD Modified" or polymeric concrete, see (*3*)). This overlay is installed utilizing the broom and seed method, similar to Flexolith 216. Installation of the overlay begins with the application of a liquid primer, Degadur B-71, to the deck with rollers. The mixed resin, consisting of Degadur 330BD (30%) and silica flour and basaltic sand (70%), is then spread on the deck with squeegees. The silica flour must all pass a #200 screen. The basaltic sand ranges primarily in size from #30 to #50. Aggregate is broadcast by hand onto the newly laid resin mixture to improve skid resistance. This aggregate, also a basaltic sand, must pass a #4 screen, but be retained on a #100 screen. MDT specifically requires that a mixture of Oregon Emery (Halsey, OR) and Manufacturer's Minerals (Renton, WA) products be used for the broadcast aggregate (*3*). These aggregates are specifically produced for this type of application. A seal-coat, Degadur 410, is applied with rollers after the aggregate is broadcast and the base has set-up. A dry surface is required to proceed with any of the applications (primer, base, and seal coat). Coverage thickness is designed to be 10-15 mils for the primer, 1/8 to 1/4-inch deep for 330BD, and 10-40 mils for the seal coat. The thickness of the finished product should be at least 3/8-inch thick. Traffic may be introduced following each day's activities, independent of specific layer completed.

2.2 INSTALLATION SITES

2.2.1 Bridge Characteristics

The physical characteristics of the bridges and bridge decks used in this study are summarized in Tables 2.2.1 and 2.2.2, respectively. With the exception of the bridge on the 19th Street Interchange in Bozeman, all of the structures were existing bridges between 16 and 31 years of age at the time of installation. The bridge at the 19th Street Interchange was new when it was overlaid with MMA. The bridges over the Gallatin River had been sealed with a silane sealer approximately 3 years before this project. The Madison bridges received a high molecular weight methacrylate approximately 2 years prior to this project. All of the remaining surfaces were the original decks, which had never been overlaid or treated with any other material. Surface conditions varied for these structures from newly constructed to having numerous previous repairs.

Table 2.2.1: Physical Characteristics of Bridges Studied.

Bridge	Overlay Treatment	Number of Spans	Maximum Span Length	Stringer Type*	Date Constructed
Gallatin	Thorotop HCR	4	51.5 ft.	P/CB	1965
West Garrison	Thorotop HCR	7	107.5 ft.	P/CB	1979
Galen	Silica Fume	3	61.5 ft.	P/CB	1978
Madison	Flexolith 216	11	71.5 ft.	P/CB	1964
East Garrison	Flexolith 216	5	148.0 ft.	SMS	1979
Fairmont	Degadur 330BD	5	51.5 ft.	P/CB	1964
19th Street	Degadur 330BD	4	108 ft.	P/CB	1995

*P/CB - Prestressed Concrete Beam, SMS - Steel Multiple Span

Table 2.2.2: Deck Characteristics, Before Overlay Installation (information provided by MDT).

Bridge	Overlay Treatment	Direction of Travel*	Deck Characteristic				
			Length (feet)	Width (feet)	Super elev. (%)	NBIS** Condition Rating (1993)	Average Cover on Reinforcing Steel (inches)
Gallatin	Thorotop	EB	205	38	<1	7	2.1
		WB	205	38	<1	7	1.7
W. Garrison	Thorotop	EB	675	42	7	7	2.3
		WB	710	42	7	7	2.1
Galen	Silica Fume	EB	133	42	2	6	1.5
		WB	133	42	2	6	1.6
Madison	Flexolith	EB	735	28	2	7	1.6
		WB	634	28	2	7	1.3
E. Garrison	Flexolith	EB	598	42	7	6	2.6
		WB	584	42	8	6	2.4
Fairmont	Degadur MMA	EB	211	38	4	7	1.9
		WB	211	38	4	7	1.8
19th Street	Degadur MMA	Both	337	57	2	New Structure	2.4

*EB - Eastbound; WB - Westbound
**NBIS - National Bridge Inspection Standards

2.2.2 Conditions of Use

Traffic data for the structures receiving the various overlay treatments were provided by MDT for 1994 and are summarized in Table 2.2.3. These data were collected from visual and automated vehicle classification counts in the vicinity of, but not necessarily directly at, each structure. Traffic varied from 3,000 to 4,500 average daily traffic (ADT). Data on heavy vehicle use is also presented in Table 2.2.3, where heavy vehicles are defined as any vehicle FHWA Class 5 or larger. The traffic data were used to calculate AASHTO equivalent single axle loads (ESALs) by MDT, and this information is also presented in Table 2.2.3.

The average climatic conditions near each installation site, as obtained from "MAPS Atlas" (a climatological data base for Montana (*8*)), are summarized in Table 2.2.4. The locations experience temperature extremes up to approximately 105°F each summer and down to -45°F during the winter. The mean annual air temperatures range from 41 to 44°F. Annual precipitation amounts range from 10 to 20 inches; annual snow fall, from 25 to 100 inches.

Table 2.2.3: Traffic Data (1994)

Location	**Direction of Travel**	**Overlay Treatment**	**ADT**	**Percent Heavy Trucks**	**18 kips ESAL*** (per day)
Gallatin	EB	Thorotop HCR	4000	23.2	1566
Gallatin	WB	Thorotop HCR	4000		1566
W. Garrison	EB	Thorotop HCR	3830	22.3	1381
W. Garrison	WB	Thorotop HCR	3140		1193
Galen	EB	Silica Fume	3960	21.8	1451
Galen	WB	Silica Fume	3240		1187
Madison	EB	Flexolith 216	3900	22.5	1531
Madison	WB	Flexolith 216	3900		1531
E. Garrison	EB	Flexolith 216	3700	21.7	1379
E. Garrison	WB	Flexolith 216	3040		1129
Fairmont	EB	Degadur MMA	4550	20.6	1635
Fairmont	WB	Degadur MMA	4550		1635

*ESAL - Equivalent Single Axil Load

Table 2.2.4: Climatic Data (adapted from (*8*))

Location	Overlay Treatment	Freeze Free Days Annually	Mean Annual Temperature (°F)	Mean January Minimum Temperature (°F)	Mean July Maximum Temperature (°F)	Average Annual Precipitation (Inches)	Average Annual Snowfall (Inches)
Bozeman	Degadur MMA	90-100	43	11	82	18-20	50-100
Gallatin	Thorotop HCR	115-120	44	10	86	12-14	25-50
Madison	Flexolith 216	120-125	44	10	85	10-12	25-50
Fairmont	Degadur MMA	70-90	41	9	80	12-14	25-50
Galen	Silica Fume	70-90	42	10	81	12-14	25-50
Garrison	Thorotop HCR, Flexolith 216	90-100	41	9	82	10-12	25-50

3. OVERLAY INSTALLATION

3.0 GENERAL REMARKS

Overlay installation spanned 2 construction seasons (see Table 2.0.1). The 1995 construction season saw the completion of the bridges with the Thorotop HCR, Flexolith 216, and Degadur MMA technologies. Installation of the remaining technology, silica fume concrete, occurred in 1996. The contractor for all bridges overlaid under IM 0002(50) was COP Construction Co., Billings, Montana. Tamietti Construction, Great Falls, Montana was the contractor for the 19th Street Bridge.

Site preparation for all bridges involved mobilizing traffic control, setting up a staging area, and replacing guard rail as required. The surfaces of all of the 1995 decks were prepared in identical fashions. The surfaces were shotblasted, any oil and asphalt spots were sandblasted, and the paint stripes were removed by jackhammering, burning and scraping, sandblasting and/or sanding. Areas requiring Class A and Class B repairs, as defined in the contract documents (*3*), were found utilizing chain drag techniques and marked by MDT inspectors. The contractor then jackhammered these spots to the satisfaction of the inspector. Any exposed rebar was sandblasted. The repair site was then filled with a patch material.

Surface preparation for silica fume (1996 construction season) consisted of milling and scarifying the surface to a depth of 0.25 to 0.5 inches. The edges near the approach and departure guard angles, as well as those along the curbs, were jackhammered to similar depths. Class A and B repairs were located via the same chaining technique employed on the other decks. Repairs were made with a concrete mixture with a rough finish.

With the decks appropriately prepared, the contractor proceeded with the overlay process. Operations used during the overlay varied with the different technologies. Details of the processes are covered in the sections devoted to the individual technologies.

Throughout this process, extensive documentation was collected on conditions prior to installation, the specifications for each installation, the products, and the results of any quality control testing. The specific information to be collected under the statement of work included:

Documentation of pre-installation conditions (Task 1):
- Electric half-cell potentials (ASTM C876)
- Chloride ion content profiles (ASTM C1218)
- Location of cracks and patches
- Permeability to chloride ions (AASHTO T277)
- Pre-installation photographic record

Documentation of the specifications for each installation (Task 2):
- Site preparation and pre-overlay repairs
- Surface preparation
- Overlay technology selected
- Overlay design life
- Mixture proportions
- Binder-to-aggregate ratio
- Pot Life (ASTM C881)
- Tensile strength (ASTM D638)
- Tensile elongation (ASTM D638)
- Viscosity (ASTM D2393)
- Minimum compressive strength at 3 hrs. (ASTM C109)
- Minimum compressive strength at 24 hrs. (ASTM C109)
- Minimum adhesion strength at 24 hrs. (VTM-92, ACI 503, or equal)
- Curing shrinkage (ASTM C596 or ASTM C883)

Documentation of the results of any job control testing or quality assurance (Task 3):
- Mixture proportions and characteristics of ingredients
- Record placement time
- Record climatic conditions during placement
- Binder-to-aggregate ratio
- Thermal coefficients of deck and overlay material
- Pot Life (ASTM C881)
- Tensile strength (ASTM D638)
- Tensile elongation (ASTM D638)
- Viscosity (ASTM D2393)
- Min. compressive strength at 3 hrs. (ASTM C109)
- Min. compressive strength at 24 hrs. (ASTM C109)
- Min. adhesion strength at 24 hrs. (VTM-92; modified ACI 503)

The items under Task 1 were generally completed by MDT. MSU was responsible for the mapping of the cracks and patches and the pre-installation photographic record. Specifications collected under Task 2 were collected from the contract documents (*3*) and manufacturers' literature (***4***, ***6***, ***7***). In general, all of the items called for under Task 3 were covered using the documentation provided

by the manufacturers. Data was collected on the placement times and climatic conditions for each installation. Values for relative humidity were gathered from the closer of the National Weather Service stations in either Bozeman or Butte, Montana. Quality control testing under Task 3 was completed for the silica fume concrete. All available information for Tasks 1, 2, and 3 is presented in detail in Section 2 and Appendix A of this report. Presented below are brief narratives describing the installation of each overlay, including information on the particular materials and methods used, when these items were not specifically dictated by the contract documents.

3.1 OVERLAY INSTALLATION

3.1.1 Thorotop HCR (Gallatin River and West Garrison Bridges)

The Gallatin Bridge was overlaid between August 8 and August 15, 1995 using Harris Specialty Company's Thorotop HCR. Representative photographs of the Gallatin bridge, before and after overlaying, are presented in Figure 3.1.1. This deck had several shallow delaminations that had to be repaired prior to the installation of the overlay. Specific locations of these and other minor repairs are given on the pre-installation distress maps presented in Appendix A.

The Thorotop HCR material, consisting of the liquid Thoro polymer and Thoro HCR powder, was mixed on-site in continuous batches. These materials were typically mixed for approximately 5 minutes, sprayed onto the deck, and spread with squeegees (see Figure 3.1.1, Photo 3). Thorotop is placed in two lifts, with the first lift placed on a moist surface. A broom finish was applied to the first lift to promote bonding between the first and second lift. Note that the Thorotop polymer and powder were mixed on the deck, itself, in the area immediately preceding the point of application of the overlay. Polymer was occasionally spilled on the untreated deck during the mixing process as it was dispensed from its storage barrels.

Placement at the Gallatin began on the west end of the eastbound driving lane. River water, delivered by fire-hose, was used to saturate the entire lane before the first application. Application of Thorotop began when the deck had dried to the point that "dry" spots began to appear. The lift started thin, but thickened progressively as the contractor became familiar with the product. Based on calculations by the contractor, the first lift was only about 1/16-inch thick. Representatives from Harris Specialty Chemicals, the product provider, did not express concern over the thinness of the

Photo 1: Pre-installation, westbound Gallatin.

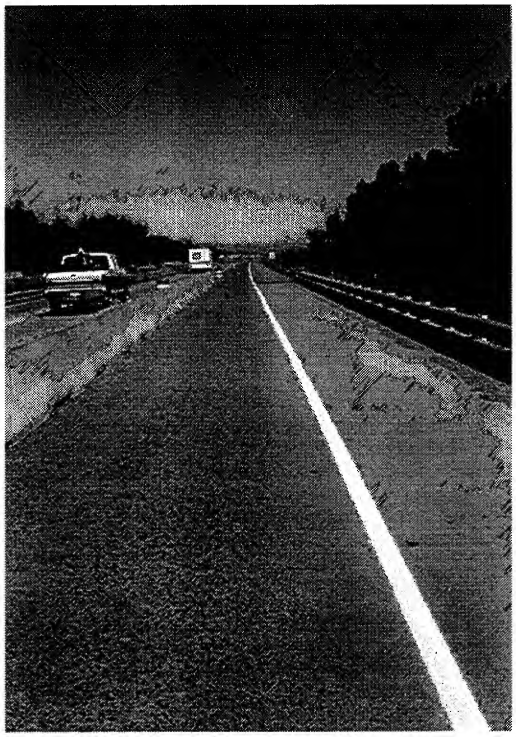


Photo 2: Pre-installation, typical driving surface, Gallatin.

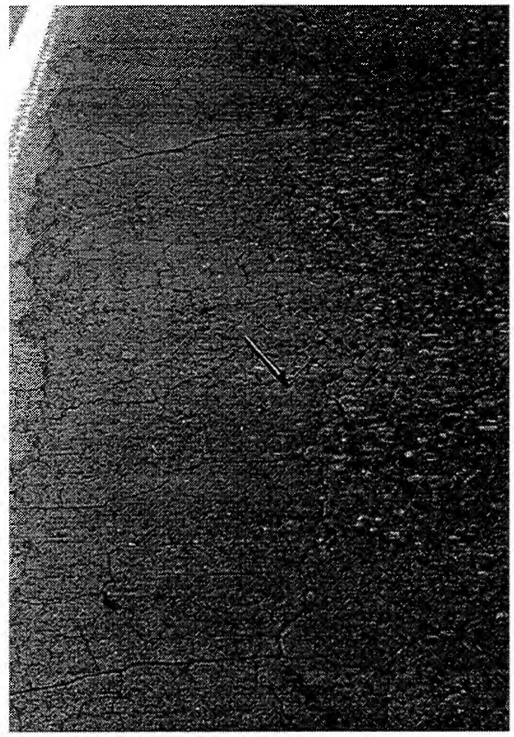


Photo 3: Thorotop HCR installation, Gallatin River.

Photo 4: Completed Thorotop HCR overlay, pre-traffic, Gallatin.

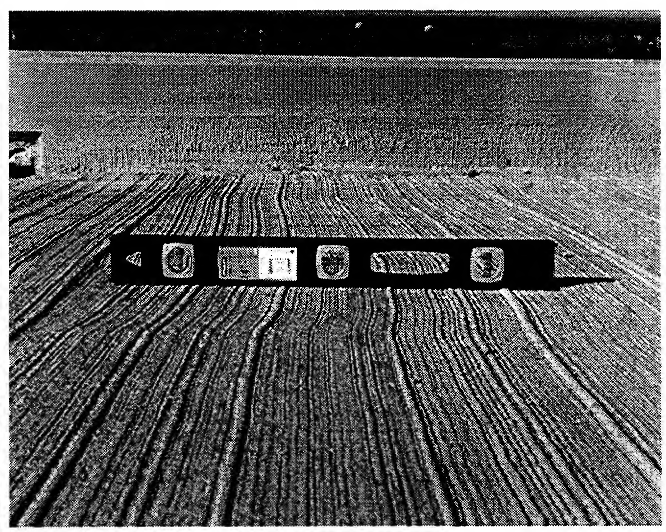


Figure 3.1.1: Gallatin Photographs - Thorotop HCR.

lift. They were comfortable with thickening the second lift to compensate for the thin first lift. The second lift on the eastbound driving lane was done on the same day as the first lift. A ridged broom finish was used on the second lift, perpendicular to the direction of travel. This finish was produced using a Baker Broom (Abilene, TX), which consisted of a single row of plastic bristles mounted on a steel rake. Traffic was introduced to the eastbound driving lane 41 hours after the completion of the second lift. A small amount of spalling, approximately 12 inches by 2 inches, extending to the original deck surface, was first noted on this deck 2 days after traffic reintroduction. This spalling occurred on the west edge in the shoulder of the lane.

The westbound driving lane was the next area of application. Both lifts were completed on the same day. A hand-held fertilizer distributor was used to wet the surface of the lane. Only the area immediately in front of the application was wetted, rather then wetting the entire surface at once, as was done for the eastbound driving lane. A delamination was located by one of the manufacturer's representatives in the westbound driving lane's second lift. An improperly washed polymer spill was the cause of the delamination. The contractor removed material in a 12.5 inch by 9.5 inch rectangular area around the delamination. This spot was then refilled with the necessary amount of Thorotop HCR and properly finished. The westbound lane was opened to traffic 3 days after the completion of the delamination repair.

The eastbound passing lane was the next surface to receive an overlay. The second lift was applied on the same day as the first. This lift received the same broom finish as had been applied to the driving lanes. The initial 20 feet of this lift seemed wetter then had the previous lifts or the remainder of this lift. Traffic was reintroduced 4 days after application.

The final surface of the Gallatin bridges to be overlaid with Thorotop HCR was the westbound passing lane. The second lift was again completed on the same day as the first. Traffic was reintroduced 3 days after application was completed.

The West Garrison Interchange was the next bridge finished with Thorotop HCR. Overlay operations took place September 18 through October 11, 1995. Photographs of the West Garrison bridges are presented in Figure 3.1.2.

The first lane of the West Garrison structures to receive Thorotop HCR was the westbound driving lane. The first attempt at application was made under poor weather conditions. These conditions consisted of strong winds, threatening skies, and a temperature of 54°F. Inspectors from

Photo 5: Pre-installation, westbound West Garrison.

Photo 6: Pre-installation, typical driving surface, West Garrison.

Photo 7: Completed Thorotop HCR overlay, pre-traffic, West Garrison.

Figure 3.1.2: West Garrison Photographs - Thorotop HCR.

MDT forced the contractor to cease operations after about 60 feet of deck had been overlaid with one lift. MDT subsequently required a shotblasting of all the applied material prior to further application. The following day, a second lift was applied to the first section and continued as a first lift for the rest of the deck. The second lift was started on the same work day as the first lift, but it was completed the following morning. Points of concern for this deck are that the surface did not appear as free of oil residue as had prior surfaces; the overlay material for the first 30 feet of the second lift appeared "dry"; and many polymer spills were noted on the second lift. Traffic reintroduction occurred 7 days after application was complete. The reintroduction was delayed compared to other Thorotop installations (which were typically opened to traffic after 3 to 4 days) due to cool weather and relatively low temperatures which slowed the curing of the overlay material.

The application of Thorotop HCR to the eastbound driving lane was done in two sections. The first section consisted of the initial 500 feet from the west; the second, the remaining 210 feet. The second lift on the initial 500 feet was completed on the same day as the first lift. Polymer was again spilled on the deck during the first lift. The first lift did not appear to be sufficiently setup to allow foot travel, especially in the shaded area along the curb, when the second lift was applied. The contractor estimated the quantities used in mixing the materials for the last 10 feet of the second lift. A delamination was discovered when the deck was chained. Unfortunately, the size and location of the delamination was not recorded. The delamination was repaired in a similar fashion to the delamination found on the Gallatin River. The completion of the eastbound driving lane was uneventful. The only item that caused concern was the possible lack of adequate curing along the curb of the first lift before placement of the second lift, as had happened in the initial 500 feet of this lane. Traffic reintroduction occurred about 4 days after application was complete.

West Garrison's westbound passing lane was the next deck surface to receive its overlay treatment. The first 30 feet of the first lift appeared thin, and a large polymer spill occurred along the south curb from 100 to 230 feet from the west end of the bridge. The second lift on the westbound passing lane was done on 2 consecutive days. All but the final 235 feet of the second lift were done on the same day as the first lift. Completion of the second lift was delayed by mechanical problems. The pump for the distribution system failed and had to be replaced. Operations resumed after the equipment was repaired, and the lift continued until work halted at the end of the day, 235

feet from the end of the bridge. Similar to the driving lanes, a strip approximately 1-foot wide next to the curb cured slowly due to the cool temperatures and shade in this area. The second lift was completed the following morning. There was at least a 5 day wait before traffic was reintroduced.

The final deck to receive Thorotop HCR was the eastbound passing lane at the West Garrison Interchange. Placement started on the west end and worked east to the second expansion joint. Placement of these lifts was uneventful. At least 4 days passed before traffic was reintroduced.

3.1.2 Silica Fume Concrete (Galen Interchange)

Silica fume concrete overlays were placed on 2 bridges located at the Galen Interchange (see Figure 3.1.3). These overlays were installed July 15 through July 29, 1996. The performance of the mix design for the silica fume concrete (see Table 2.1.2) was confirmed by testing by Maxim Technologies of Billings, Montana, as required in the contract provisions (*3*). The silica fume utilized on this project was Rheomac SF 100. The silica fume was added at a rate of 25 lbs./sack of cement, which is more than three times the minimum rate of 7.5 lbs./sack given in the mix design (note that Maxim's mix confirmation was done using 7.5 lbs./sack). A water reduction agent, Prokrete N/USA, was used at the rate of 4 ounces per bag of cement. The air entraining admixture was MB VR Standard. The evaporation retardant was Confilm (a product which is sprayed on to the surface of the unfinished concrete to minimize evaporation). All of these items are products of Master Builders, Inc. (Cleveland, OH). Holnam, Inc. (Three Forks, MT) furnished the Portland Cement, Type I-II. The aggregate was obtained from the Bud Campbell Pit (Deer Lodge, MT).

Preparation of the structures consisted of milling and scarifying their surfaces to depths of 0.25 to 0.5 inches. The edges near the guard angles and along the curbs were jackhammered to similar depths. A 1-inch thick steel plate was welded on top of the existing guard angle, so that the elevations of the finished overlay and the guard angles were the same. All Class A and B repair sites were initially filled with Speed Crete, a quick setting Portland cement concrete from Tamms Industries. When the contractor ran out of Speed Crete, approval was given by MDT to complete all remaining repairs with silica fume modified concrete. Irrespective of the material utilized, the repair areas were given a rough finish to promote bonding with the overlay, coated with a curing compound, and covered with wet burlap bags and plastic. These areas were cured for a minimum of 4 days prior to overlay application. The last preparatory activity was a final shotblasting of the repair areas to further roughen their surfaces.

Following the preparation and repair of the decks and curing of repair areas, the overlay process began (see Figure 3.1.3, Photo 9). Application was made in a single lift. Both driving and passing lanes were completed at the same time. A power screed was utilized for the placement. Climatic conditions were measured by the MDT (see Appendix B). Traffic reintroduction occurred after a minimum of 6 days of curing.

Quality control testing performed by MDT for the silica fume overlays included measurements of the slump, air entrainment, and 4-day, 14-day, and 28-day compressive strengths of the concrete. A summary of the results of this quality control testing is given in Appendix B. The average 28-day compressive strength of all test cylinders taken (independent of the specific batch) was 7554 psi, with a standard deviation of 643 psi. Two of the six 28-day tests which were performed were below the required strength of 7500 psi (6373 and 7451 psi).

Photo 8: Pre-installation, westbound Galen.

Photo 9: Silica fume installation, Galen.

Photo 10: Finished silica fume.

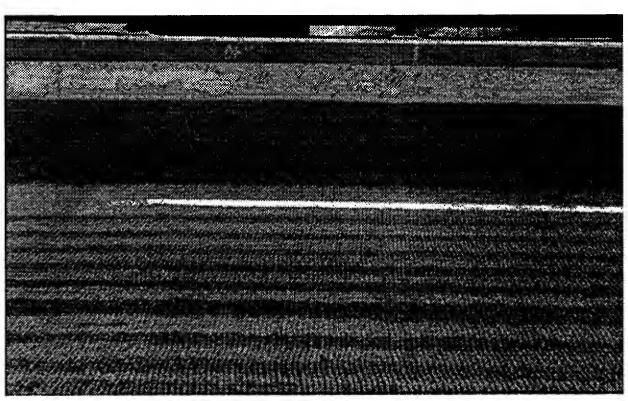


Figure 3.1.3: Galen Photographs - Silica Fume.

3.1.3 Flexolith 216 Epoxy (Madison and East Garrison Interchange)

The Flexolith overlays on the Madison and East Garrison bridges were installed in 2 lifts; no seal coat was used. Overlay preparation for these bridges was identical to the preparation for the Thorotop HCR bridges. Note that the Madison River bridges generally had more previous repairs to the decks than the other bridges investigated.

The bridge over the Madison River was overlaid between August 23 and September 1, 1995. Photographs of the Madison bridges are presented in Figure 3.1.4. The contractor decided to apply the overlay at the Madison River to one half of a lane at a time. Work began on the east end of the bridge on the inside half of the westbound driving lane. Equal parts of base and hardener were mixed for 3 minutes, in 5 gallon or larger batches. Smaller batches were mixed as the temperature increased to insure all the material could be placed before it set (set time decreased with increasing temperatures). The mixed material was poured onto the dry deck surface. The mixture was then spread with squeegees to a uniform depth (see Figure 3.1.5, Photo 16). The overlay was placed in 2 lifts of approximately equal thickness. Aggregate, supplied by Oregon Emery, was broadcast by hand onto the surface of each lift. After each lift cured sufficiently, the excess aggregate was removed by sweeping the surface. Prior to the application of the first lift, duct tape was placed longitudinally down the center of the lane to provide a sharp seam between the 2 installations required to complete each lane. When the material had acquired its initial tack, this tape was removed.

An extended amount of time was required to lay down the first lift, and work was halted on this lift at the sixth bent, about 325 feet west of the starting point. A second lift was then applied to that portion of the first lift that had been completed. The end of the first batch of epoxy on the second lift began to set up prematurely. This material was quickly removed with flat shovels, and the area redone. It started to rain 4 hours after the second lift was completed.

A re-evaluation of the construction procedure led to the application of the overlay to the entire width of a lane using 10 gallon batches. This approach drastically improved productivity. After 30 feet of the second lift had been completed, the threat of rain forced a shut down of activities. This portion of the deck was covered to protect it from the impending rain. Work could not resume the next day, which was a Friday, due to continued rain. The second lift was finally completed on

Photo 11: Pre-installation, westbound Madison.

Photo 12: Pre-installation, westbound Madison.

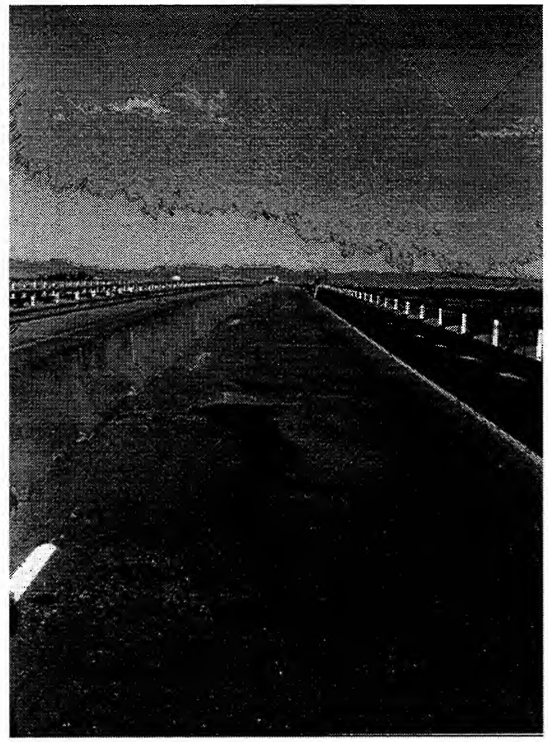


Photo 13: Completed Flexolith 216 overlay, pre-traffic, Madison River.

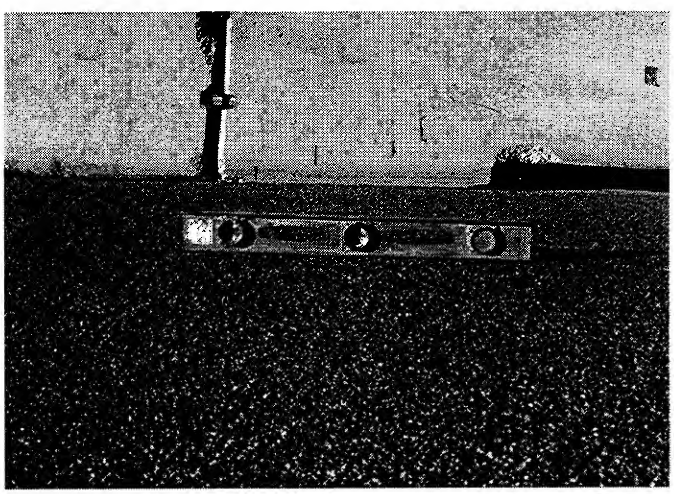


Figure 3.1.4: Madison Photographs - Flexolith 216.

Monday. The final 30 feet remained to be completed when the contractor ran out of material. This small area was subsequently completed later that day. In applying this lift, there was a leak in the bucket used to mix the epoxy. A trail of epoxy was left on the deck when the bucket was moved from the mixing area to where it was poured. This trail then dried to varying degrees before the crew caught up to it. Water was discovered on the deck during the application. The water came from a fresh water jug on one of the contractor's vehicles. It was also noticed that the aggregate was moist as it came out of the supply bag. This bag was immediately removed, but the first half of its contents had already been used. Traffic was allowed on the westbound driving lane approximately 23 hours after completion.

The eastbound driving lane was the next area to receive Flexolith 216. The application process for this lane was interrupted several times. The first lift began on the west end and stopped at the seventh bent about 370 feet to the east. The second lift extended only to the third bent, about one hundred feet east of the starting point. On the following day, the second lift was resumed from the third bent. Progress continued on what was now a first lift past the seventh bent until the contractor ran out of emery about 30 feet from the end of the bridge. Emery was collected from the staging area, and the lift was completed. The second lift, from the seventh bent on, was then completed. Traffic reintroduction occurred 72 hours after completion of the second lift.

The westbound passing lane was the next application site. The contractor began preparing the deck in the morning and completed the 2 lifts in 1 day. The finish of this deck is similar to that of the other lanes, but there is an area, near the seventh bent, approximately 1 foot by 3 feet, in which the surface aggregate was noticeably sparse. This lane also appeared to have less aggregate coverage overall, compared to the other lanes.

MSU representatives were only present for the application of the first lift to the eastbound passing lane. A point of concern on this application was the repeated occurrences of individuals walking in the epoxy with flat soled shoes as it was being placed. The manufacturer's representatives stated that walking in the fresh material was acceptable only with spiked shoes.

The second Flexolith 216 site was the East Garrison Interchange (see Figure 3.1.5). These bridges were overlaid between September 6 through September 14, 1995. Work began with the

Photo 14: Pre-installation, eastbound East Garrison

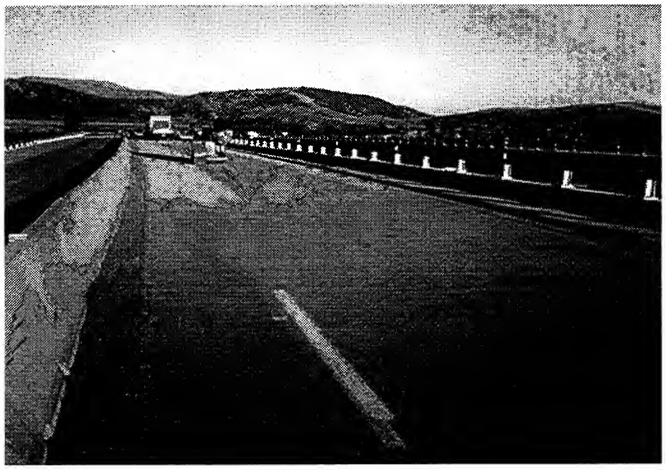


Photo 15: Pre-overlay, surface, East Garrison.

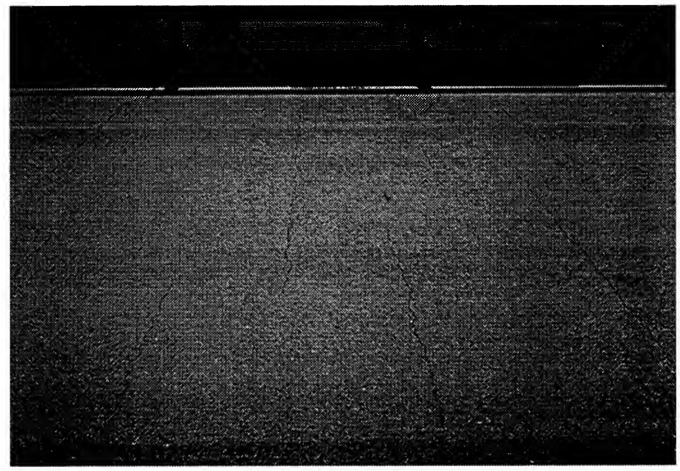


Photo 16: Flexolith 216 installation, East Garrison.

Photo 17: Completed Flexolith 216 overlay, pre-traffic, East Garrison.

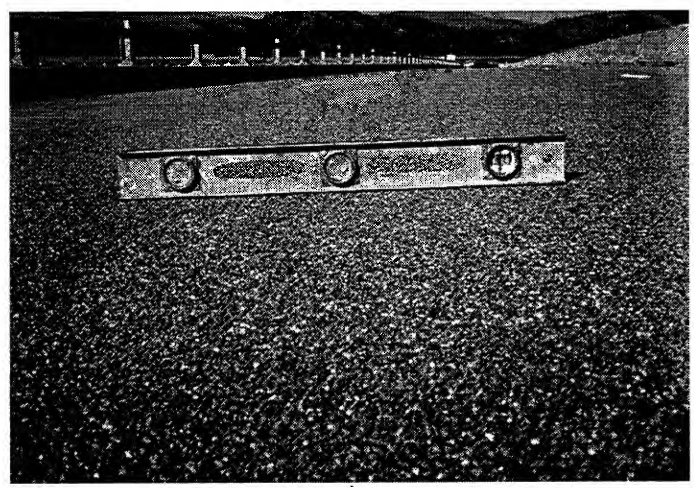


Figure 3.1.5: East Garrison Photographs - Flexolith 216.

application of the first lift to the westbound driving lane. Silica from the sandblasting was still present in the existing popouts in the original deck surface when this lift was applied. For the second lift, increasingly ominous skies stopped the contractor at mid-span. Work on the second lift resumed the next morning. Water from the rains of the previous night was removed using a propane torch.

Traffic was reintroduced the day after the second lift was completed. Concerns of note are that the aggregate used on the second lift was the swept aggregate from the first lift (some of this aggregate was already partially coated with Flexolith), the lack of testing for the moisture content of the deck prior to overlay application utilizing the "visqueen test" (ASTM D-4263) (*9*) called for in the manufacturer's installation procedure (*6*), and the continued problem of the workers walking in the epoxy with flat soled shoes.

The eastbound driving lane was the next lane to receive the overlay. Wet spots left by the previous night's rain were again dried using a propane torch. After about 30 minutes, it was noticed that the aggregate was moist. Epoxy had already been spread for the first lift when this situation was noticed, and it sat for about fifteen minutes (at temperatures of 61°F (ambient) and 71°F (deck)) while a new bag was retrieved. In addition to the moisture in the aggregate, there appeared to be moisture in the cracks over the bents. The second lift was done under similar climatic conditions as the first. Wet aggregate resulted in delays in placing this lift. Potential problems with this application include that the first lift was swept when the material next to the curb still appeared gummy; unknown quantities of the 2 parts to the epoxy were dripping from the contractor's truck onto the deck; and the first lift did not appear fully set when the second lift began. Moreover, visual inspection indicated poor aggregate coverage on the second lift, as indicated by "wet" spots. Traffic reintroduction occurred less then 18 hours after the completion of the second lift.

The westbound passing lane was the next lane treated. The first lift was completed without problems. The second lift was finished the next day. The only concern for this lane was the large number of "wet" spots in the finished surface, indicating that more aggregate may have been needed. Once more, traffic reintroduction took place the following day, less then 24 hours after the second lift was completed.

The eastbound passing lane's first lift was completed on the same day as the westbound passing lane. During installation of this lift, the contractor skipped a large wet spot from a water jug spill to allow it to dry. This spot was fixed the following day before the second lift began. The second lift was completed the following day. No concerns were observed on this lift. As with most of the Flexolith 216 lanes, traffic reintroduction occurred the day after completion of the second lift.

3.1.4 Degadur 330BD MMA (Fairmont and 19th Street)

The only remaining bridges treated in 1995 with MSU representatives on site were near the Fairmont Interchange (see Figure 3.1.6). These bridges were overlaid with Degadur MMA 330BD from September 26 to October 2, 1995. Only a few pictures were taken for these structures, due to the concurrent overlaying activities taking place at the Garrison structures that had to be simultaneously monitored. MMA was applied in three lifts: a primer, a base application of MMA and aggregate, and a top seal coat. The aggregate used for MMA was Basaltic Bridge Topping (Manufacturer's Minerals, Renton, WA), and the emery used with Flexolith 216 from Oregon Emery, mixed in a 2 to 1 ratio. While the contract documents (*3*) specified these aggregates be mixed by the supplier, mixing was done by the contractor.

Preparation of the deck surface was identical to that for the other 1995 overlay treatments. Shotblasting was the primary preparation tool. Paint stripes and edges were treated with hand-held jackhammers.

Application of the primer began with the westbound passing lane. Rollers were used for the bulk of the application (see Figure 3.1.6, Photo 18). Brushes were used along the curb and guard angles and in areas with depressions. The eastbound passing lane received its primer coat on the same day as the westbound lane. The base application of Degadur was made on the westbound passing lane the following day. The seal coat for the westbound passing lane was applied following the completion of the base. Application of the base material and seal coat for the eastbound passing lane occurred the following day. The westbound driving lane was primed and half of the base coat applied on the same day that the eastbound passing lane was completed. Progress was halted for the day at mid-span. Base application resumed the following morning. A light rain fell about 50 minutes after the completion of the base on the second day. No seal coat had been applied to either the material from the day before or the new material when the rain arrived. Seal coating started less than one hour after the rain quit.

Photo 18: Degadur installation, eastbound, Fairmont.

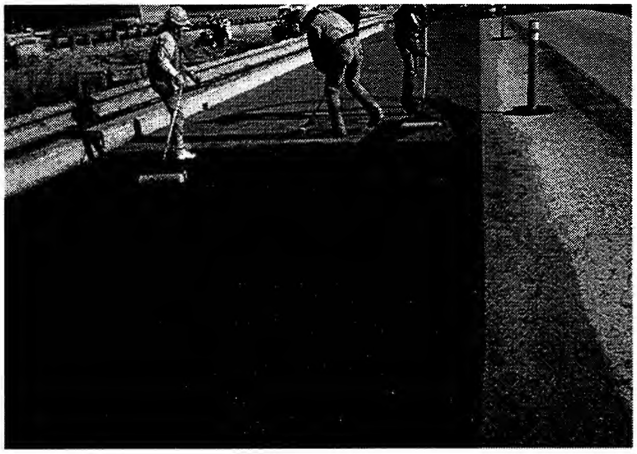


Photo 19: Completed Degadur overlay, pre-traffic, Fairmont.

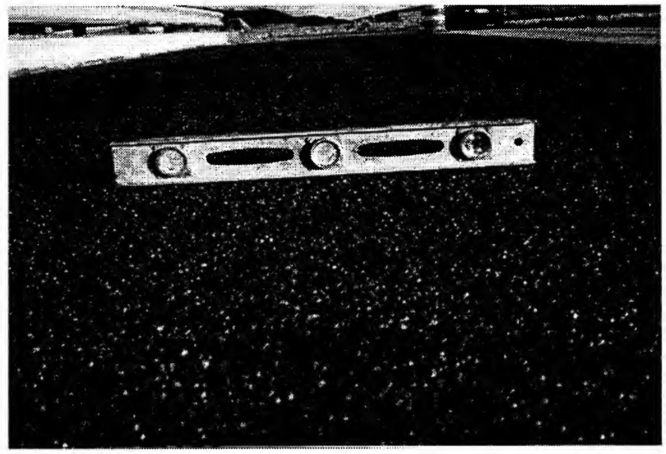


Figure 3.1.6: Fairmont Photographs - Degadur 330BD.

The eastbound driving lane was the only remaining lane to overlay. An attempt was made to begin applying the primer on the same day that the westbound driving lane was completed, but rain forced MDT inspectors to halt operations 10 minutes into the process. Application began anew 3 days later, following a weekend. A point of concern was the incompleteness of the application. Specifically, along the curb, dry spots were noticed where the primer did not completely cover the deck. Base material was applied on the same day the eastbound driving lane was primed. Application was done in 2 stages because the contractor ran out of hardener during the placement of the base. The contractor attempted to stretch the hardener for the application by reducing the amount used in each batch. They came up 55 feet short, however, of completing the base. The MDT inspectors witnessed the sealing operations, ending the MMA application.

Information on the installation of MMA on the 19th Street Interchange is limited, as this structure was added to this program after the overlay had been completed. A Degussa MMA system was used on this bridge. Overlay installation was to be performed consistent with MDT standard MMA specifications (same specifications as used for the Fairmont structures). This installation was done, in part, to improve the finish on the surface of the deck. Problems during the construction of the structure resulted in an unacceptable surface finish on the virgin deck.

3.2 OVERLAY COSTS

Bid prices for the various overlay technologies, as presented by the contractor that was awarded this project, are given in Table 3.2.1. These prices reflect the material and labor costs for the installed overlays. Pre-installation deck repair and traffic control costs are not included in these costs. The cost of the 19th Street Interchange MMA overlay is not included in the indicated MMA price.

Table 3.2.1: Installation Costs

Material	Bid Price
Thorotop HCR	\$22.00/yd^2
Silica Fume	\$40.00/yd^2
Flexolith 216	\$36.00/yd^2
Degadur MMA	\$44.00/yd^2

4. INITIAL CONDITIONS

4.0 GENERAL REMARKS

The evaluation of the initial conditions of each overlay was the combined responsibility of MSU and MDT. Characteristics of interest and the tests to be performed were established in Task 4 of the program plan. Requirements were the same for either hydraulic cement or polymer overlays and included:

Locate delaminations before opening to traffic using a chain drag method.
Measure roughness before opening to traffic using a straight edge.
Perform skid tests after 4-8 weeks of traffic.
Measure electric half-cell potential (ASTM C876) on one lane of one span before opening to traffic.
Conduct three reproducible tensile adhesion tests approximately six weeks after installation.
Conduct three AASHTO T277 permeability tests on cores approximately six weeks after installation.
Post-installation photographic record.
Report overlay costs.

All of the specified items have been completed, except for the AASHTO T277 permeability tests. MDT indicated that the likelihood of encountering reinforcing bars in the coring process for these tests was too high to justify attempting the procedure. Note that delays were encountered in performing the skid and adhesion testing required under Task 4. These delays extended beyond the desired 6-week time frame for completion of these tests. The cores produced as part of the adhesion tests were used to measure overlay thicknesses.

4.1 INITIAL PERFORMANCE TESTS

The only delaminations located prior to traffic reintroduction were found on Thorotop HCR structures. Details of these delaminations can be found in their respective installation sections. A straight edge was placed on finished surfaces and photographed to record the initial roughnesses. These photographs are included in the installation documentation in Section 3. The overlay bids reported in Section 3.3 accurately account for actual overlay costs.

4.1.1 Skid Testing

The Idaho Department of Transportation conducted a series of skid tests on the demonstration overlays from July 16 through July 18, 1996. Tests were conducted at both 40 and 50 mph with a smooth and a ribbed tire. Test results for the 40 mph tests are summarized by overlay technology in Figures 4.1.1 through 4.1.3, and in Table 4.1.1. Trends in skid resistance observed in the 40 mph test results generally are reflected in the results from the 50 mph tests, for which less data were available. Complete results for the skid testing (40 and 50 mph tests) of each bridge are given in Appendix B. Tests were conducted in accordance with AASHTO T242-92 (***10***). Age of the decks at the time of testing ranged from 9 to 14 months. Testing was done in the driving lanes of all the structures involved in this investigation except the silica fume bridges at Galen, which had yet to be overlaid, and thus, were not tested.

Referring to Figures 4.1.1 through 4.1.3, Flexolith consistently offered higher skid resistance than Thorotop HCR and Degadur MMA, independent of the specific type of test being conducted, bridge under consideration, or direction of travel. Skid numbers (40 mph tests) for Flexolith 216 averaged 56 and 47 for ribbed and smooth tires, respectively. Skid numbers for Degadur MMA and Thorotop were similar in magnitude and ranged around 42.5 (ribbed tire) and 26.5 (smooth tire). Thus, the Flexolith skid numbers exceed the corresponding values for Thorotop and Degadur MMA by about 30 percent and 80 percent for ribbed and smooth tires, respectively.

The minimum recommended 40 mph skid number for a 70 mph traffic speed is 37 (***11***). This recommendation is based on an assumed gradient (Δskid number/Δtest speed) of 0.2, a nominally conservative value for a coarse textured surface. Actual gradients could not be reliably calculated from the data collected herein, in that only 2 test speeds were used. All the overlays investigated had average, 40 mph ribbed tire skid numbers, that exceeded the minimum value of 37. Only Flexolith 216 had an average, 40 mph smooth tire skid number that was above this minimum. Comparative analysis of the skid test results (for 40 and 50 mph tests) are presented in Appendix C.

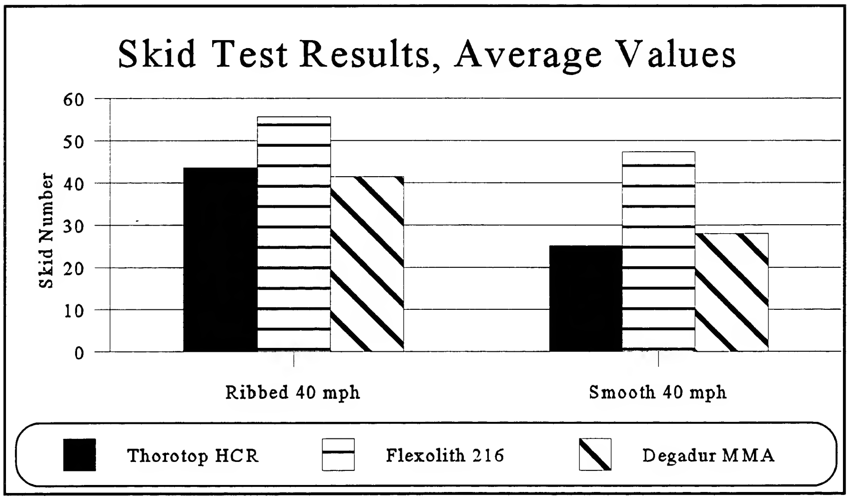


Figure 4.1.1: Skid Test Results, Average Skid Numbers for all 40 mph Tests, by Overlay and Tire Type.

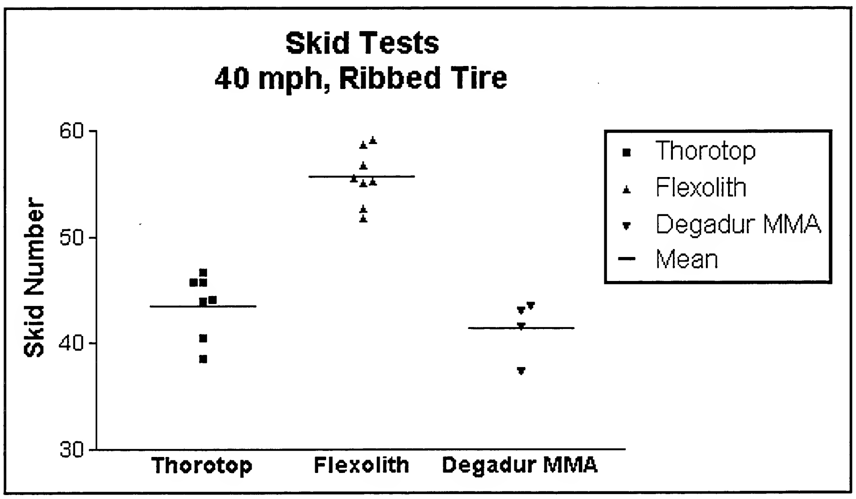


Figure 4.1.2: Individual 40 mph Ribbed Tire Skid Tests.

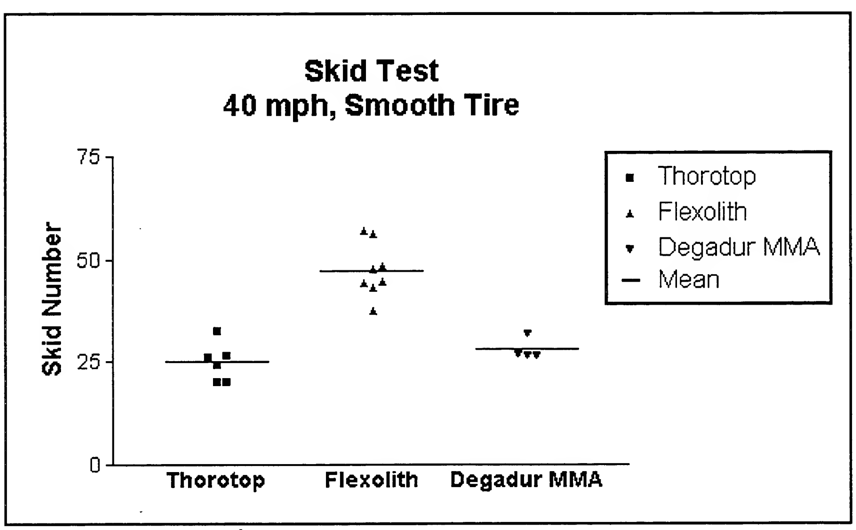


Figure 4.1.3: Individual 40 mph Smooth Tire Skid Tests.

Table 4.1.1: Skid Test Results, 40 mph Tests

Location	Direction	Tire Type	Average Skid Number
Thorotop HCR			
Gallatin	EB	Ribbed	43.9
Gallatin	WB	Ribbed	38.5
W. Garrison	EB	Ribbed	45.0
W. Garrison	WB	Ribbed	44.3
Gallatin	EB	Smooth	20.4
Gallatin	WB	Smooth	24.5
W. Garrison	EB	Smooth	26.4
W. Garrison	WB	Smooth	26.5
Flexolith 216			
Madison	EB	Ribbed	53.9
Madison	WB	Ribbed	53.7
E. Garrison	EB	Ribbed	56.0
E. Garrison	WB	Ribbed	58.9
Madison	EB	Smooth	40.9
Madison	WB	Smooth	43.9
E. Garrison	EB	Smooth	48.1
E. Garrison	WB	Smooth	56.7
Degadur MMA			
19th Street	EB	Ribbed	43.1
19th Street	WB	Ribbed	37.4
Fairmont	EB	Ribbed	43.6
Fairmont	WB	Ribbed	41.5
19th Street	EB	Smooth	31.8
19th Street	WB	Smooth	26.6
Fairmont	EB	Smooth	27.0
Fairmont	WB	Smooth	26.7

4.1.2 Adhesion Testing

Adhesion testing of the overlays was completed by MDT when time permitted during 1996 and 1997. Figure 4.1.4 shows all of the individual adhesion test results, grouped by overlay type, and a summary of the test results is presented in Table 4.1.2. Complete results for all adhesion tests are presented in Appendix B. All of the constructed surfaces have been tested with the exception of the Galen (silica fume) and 19th Street Interchanges (Degadur MMA). The surfaces of the silica fume decks were too rough to allow for proper adherence of the epoxy. The 19th Street deck will be tested in 1997. Ages of the decks at the time of these tests ranged from 10 to 15 months.

The adhesion tests were performed in accordance with the Virginia Test Method for Testing Epoxy Concrete Overlays for Surface Preparation and Adhesion (VTM-92) (***12***). There are 5 types of failure recognized by this procedure:

Type 1. Failure in the concrete at a depth greater than or equal to 1/4 inch over more than 50 percent of the test area.

Type 2. Failure in the concrete at a depth less than 1/4 inch over more than 50 percent of the test area.

Type 3. Separation of the epoxy overlay from the concrete surface.

Type 4. Failure within the epoxy overlay.

Type 5. Failure of the epoxy test adhesive.

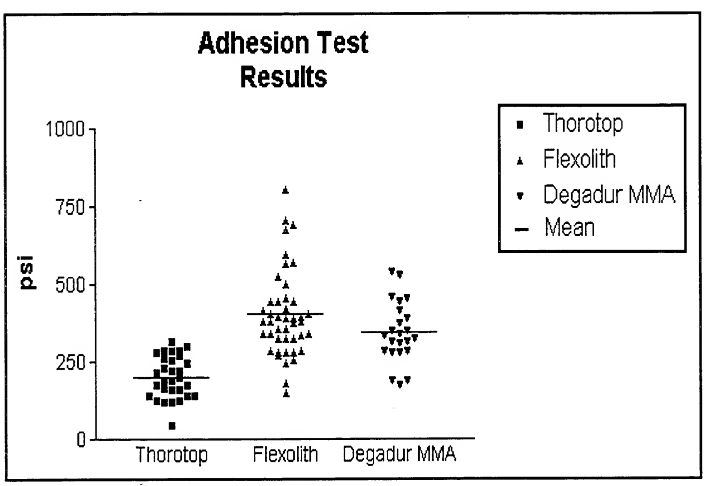


Figure 4.1.4: Adhesion Test Results

Table 4.1.2: Adhesion Test Results

Location	Failure Type(s) (Percent)					Primary Failure Type*	Average Rupture Stress** (psi)	Manufacturer's Specified Adhesion (psi)
	1	2	3	4	5			
Thorotop HCR								
WB Gallatin	100	0	0	0	0	1	222	325
EB Gallatin	100	0	0	0	0	1	262	
WB West Garrison	21.7	0	17.3	56.5	8.7	4	172	
EB West Garrison	0	0	0	100	0	4	201	
Flexolith 216								
WB Madison	56.5	26.1	4.3	0	8.7	1	602	Concrete Failure
EB Madison	100	0	0	0	0	1	344	
WB East Garrison	75.0	16.7	0	8.3	0	1	333	
EB East Garrison	50.0	16.7	0	33.3	0	1	362	
Degadur MMA								
WB Fairmont	41.7	8.3	0	0	50.0	5	295	>250
EB Fairmont	66.7	16.7	0	0	16.7	1	386	

*Account for at least 50% of the failures
**VTM-92 Test Method

Referring to Figure 4.1.4 and Table 4.1.2, rupture stresses for Flexolith 216 and Degadur MMA were of the same order of magnitude, with overall mean values of 403 and 346 psi, respectively. Statistically (at a 95 percent confidence interval), it could not be concluded that these means are different (see Appendix C). The Degadur MMA rupture stresses exceed the minimum adhesion strength for this material given by the manufacturer of 250 psi and the strength required by MDT in the contract documents of 200 psi. With the exception of the tests on the westbound deck of the Degadur MMA bridge at Fairmont, the majority of the failures in the Flexolith and Degadur structures clearly occurred in the deck concrete (Type 1 failure). Thus, Flexolith meets its manufacturer's adhesion criteria, which states that all failures must occur in the deck concrete.

The adhesion strengths for the Thorotop HCR overlays were consistently less than those for the Flexolith and Degadur MMA overlays. The rupture stresses for Thorotop averaged 202 psi, considerably below the strength of 325 psi specified for the product by the manufacturer. Note, however, that in the case of the Gallatin decks, the overlay and the overlay to deck bond were at least as strong as the deck concrete, as all of the failures occurred well into the deck concrete (Type I failure). Whether or not the overlay and bond strengths are consistent with the manufacturer's minimum expected value of 325 psi is uncertain, as the concrete failed before these elements at average stresses of 222 and 262 psi for the westbound and eastbound structures, respectively. For the West Garrison structures, failure during the adhesion tests predominantly occurred in the overlays (Type 4 failure) at stress levels significantly below the manufacturer's specified minimum value of 325 psi. Average adhesion values of only 172 and 201 psi were obtained from testing for the westbound and eastbound structures, respectively.

Note that in the above discussion, all of the adhesion values specified by the manufacturers are based on the ACI 503 test method (*13*), while all of the values reported for the demonstration decks were obtained using the VTM-92 test method (*12*). Based on a review of the test methods, the test procedures are nearly identical, and thus the adhesion values obtained using either test specification should be comparable.

4.1.3 Overlay Thicknesses

Thicknesses of the installed overlays were measured using the samples collected during the adhesion tests. A summary of the measured thicknesses is presented in Table 4.1.3. These thickness measurements were made 10 to 15 months after the overlays were installed and after 1 winter of service.

In general, at the time these measurements were made, the overlays were thinner than required by the design specifications at the time of installation (see Table 4.1.3). Measured thicknesses of the Flexolith and Degadur MMA overlays ranged from 50 to 100 percent of the initial design thickness of 3/8-inch. Thicknesses of the Thorotop overlays ranged from less than 33 percent to 130 percent of the initial design thickness of 3/16-inch. Of particular concern were the average thicknesses of the Thorotop overlay at the Gallatin structures, which were all less than 33 percent of the initial design thickness. Presuming the installation initially met the design specifications, these reductions in thickness are related to in-service wear.

Table 4.1.3: Overlay Thicknesses

Location	Material	Design Thickness (1/16 inch)	Range of Measured Thicknesses (1/16 inch)	Average Thickness (1/16 inch)	Age
WB Gallatin	Thorotop	3	<1	<1	15 months
EB Gallatin	Thorotop	3	<1	<1	15 months
WB W. Garrison	Thorotop	3	2 - 4	3	10 months
EB W. Garrison	Thorotop	3	N/A*	N/A	10 months
WB Madison	Flexolith	6	3 - 7	3	15 months
EB Madison	Flexolith	6	4 - 5	5	15 months
WB E. Garrison	Flexolith	6	3 - 4	4	10 months
EB E. Garrison	Flexolith	6	3 - 4	3	10 months
WB Fairmont	Degadur MMA	6	6	6	10 months
EB Fairmont	Degadur MMA	6	3 - 4	3	10 months

*N/A - Not Available

4.1.4 Electric Half-Cell Potentials

Measurements of the half-cell potentials on the overlaid structures were made after overlay installation and prior to the reintroduction of traffic. The results of the half-cell potential tests are presented in Figures 4.1.5 to 4.1.10. On those decks which received Flexolith 216 and Degadur (the Madison River, East Garrison and 19th Street structures), half-cell results could not be collected due to the apparent insulative nature of these products. Therefore, results are only available for the Thorotop HCR and silica fume bridges (Gallatin, West Garrison, and Galen). The tests were conducted in accordance with ASTM C876 (***14***). Temperatures when the tests were conducted were 70 to 80°F in all cases.

The occurrence of corrosion is believed to be likely if a voltage reading taken during the half-cell potential test is less than -0.35 volts copper sulfate electrode (V CSE) (***14***). In areas with readings greater than -0.20 V CSE, corrosion is unlikely. When the readings falls between these

thresholds, the occurrence of corrosion is uncertain. Reviewing Figures 4.1.5 to 4.1.10, the occurrence of corrosion is unlikely over most of the West Garrison and Gallatin structures, as at least 85 percent of the reading were above -0.20 V CSE and 100 percent of the reading were above -0.35 V CSE. Some of the readings from the Galen structures indicate that corrosion was likely to have been occurring on parts of the decks when the readings were taken. Readings that would indicate corrosion activity (<-0.35 V CSE) occurred over approximately 7 percent of the deck surface.

Figure 4.1.5: Eastbound Gallatin River Half-Cell Results

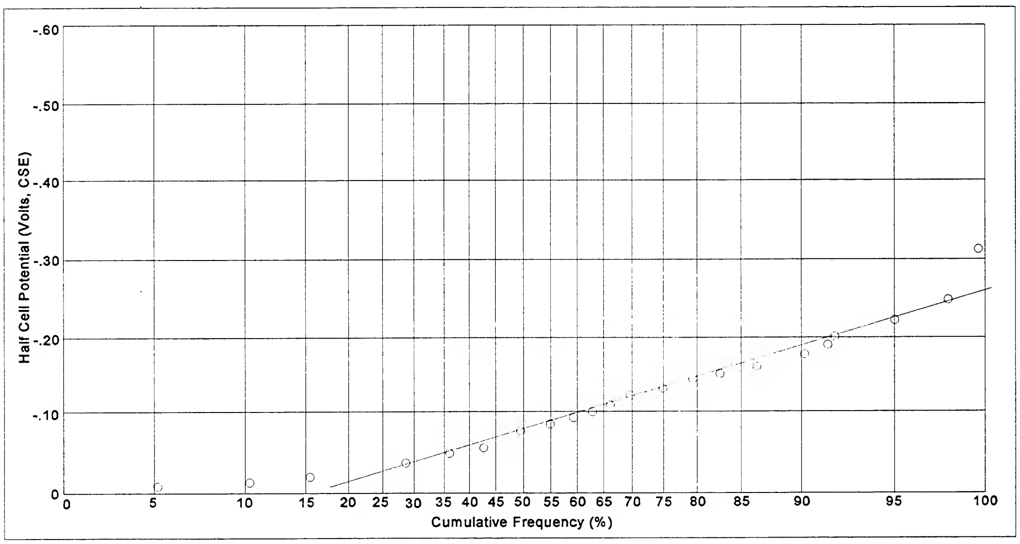


Figure 4.1.6: Westbound Gallatin River Half-Cell Results

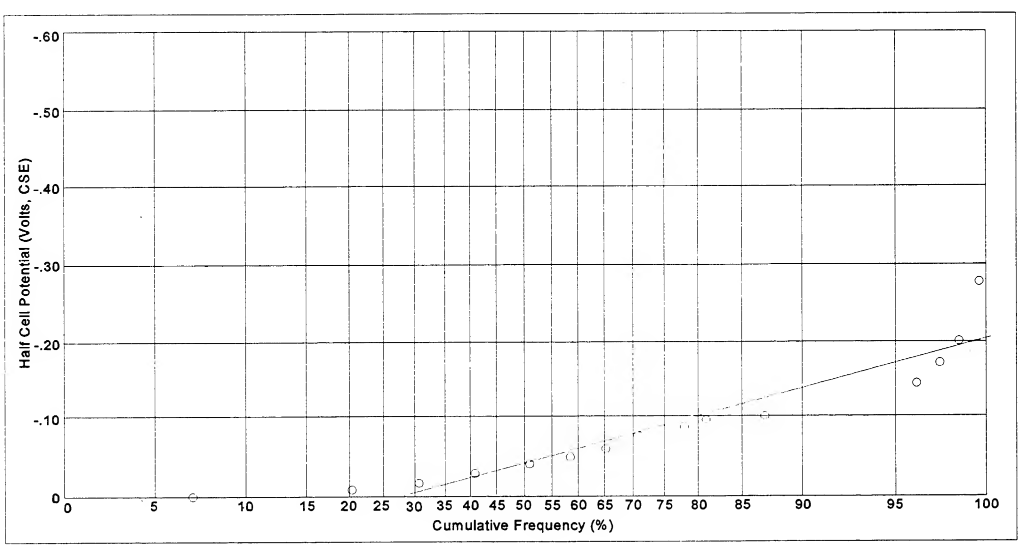


Figure 4.1.7: Eastbound West Garrison Half-Cell Results

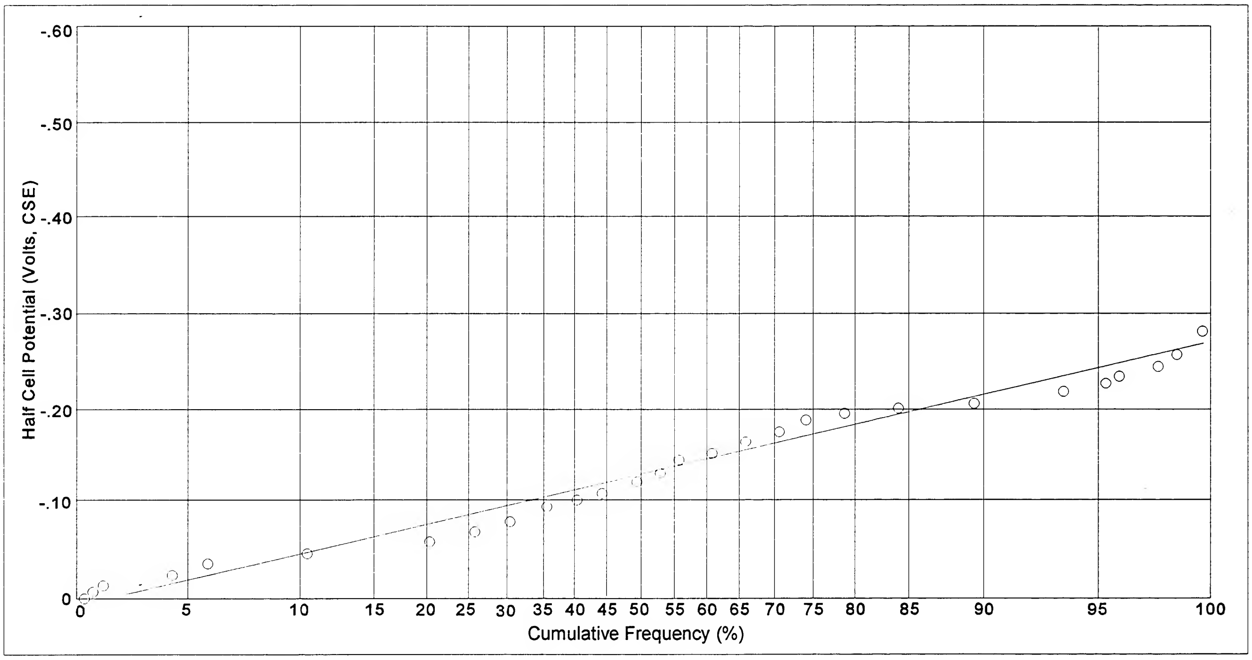


Figure 4.1.8: Westbound West Garrison Half-Cell Results

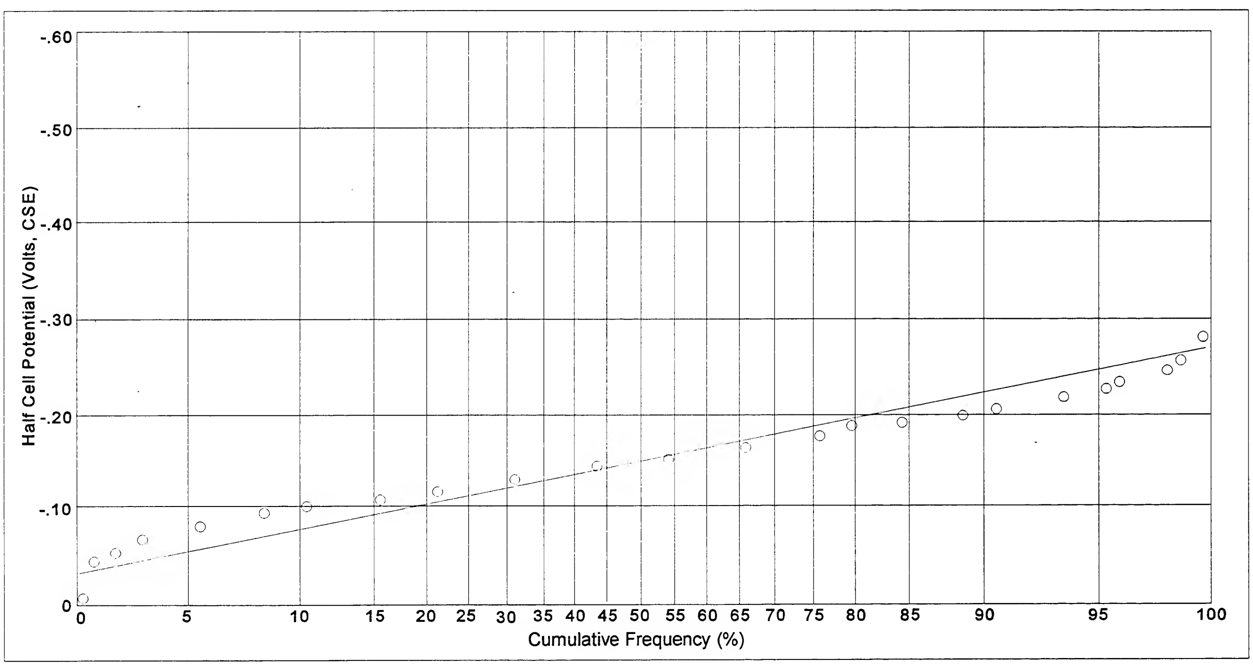


Figure 4.1.9: Eastbound Galen Half-Cell Results

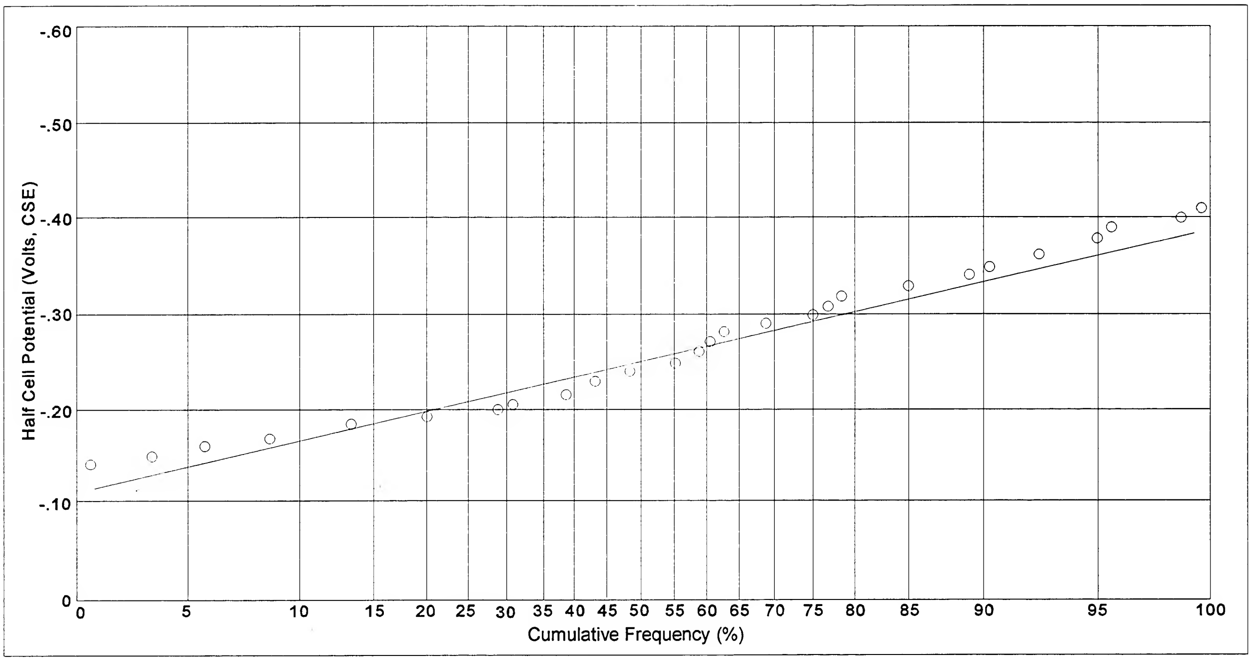
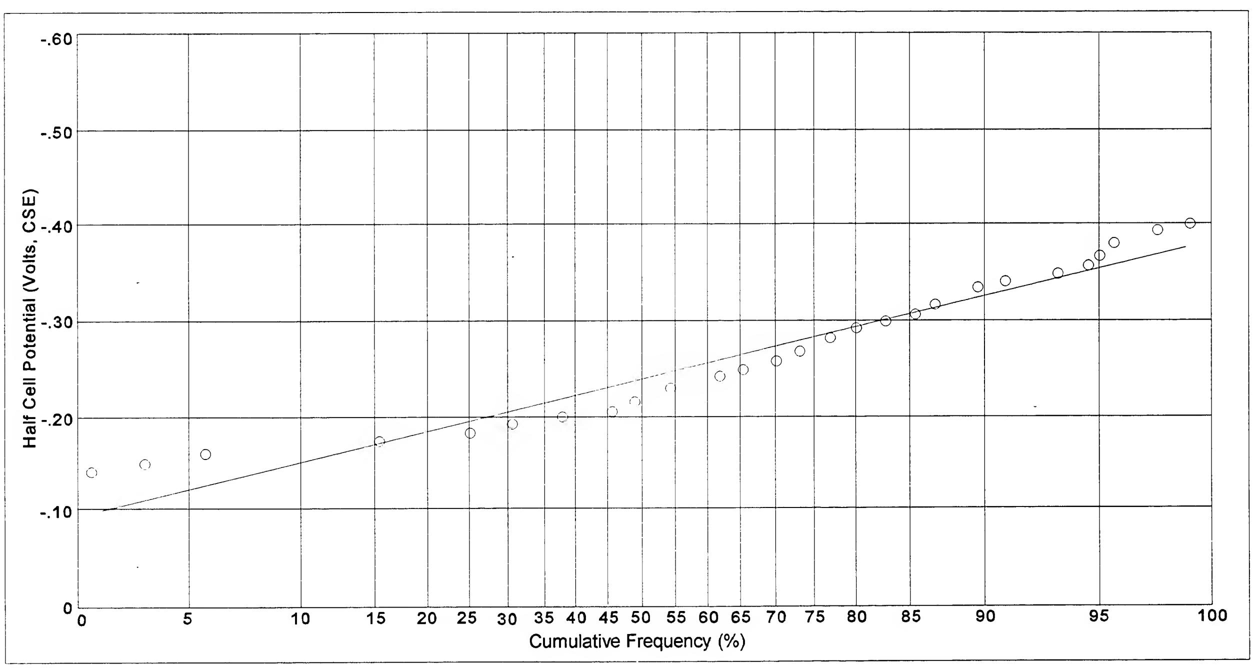


Figure 4.1.10: Westbound Galen Half-Cell Results



5. FIRST ANNUAL EVALUATIONS

5.0 GENERAL REMARKS

The first annual evaluation of the bridges overlaid in 1995 occurred on August 5, 1996. A visual inspection of the surface was made at each of the structures noting any delaminations, marring from snow plows, and general wear. The first annual evaluation of the bridges overlaid in 1996 occurred on March 21, 1997. Representative pictures were taken to document distresses and deck conditions. A summary of the observation from the first annual evaluations is presented in Table 5.0.1.

5.1 OVERLAY TECHNOLOGIES

5.1.1 Thorotop HCR

The Gallatin River structures had pronounced wheel paths visible in the westbound driving lane (see Figure 5.1.1, Photo 20). In these wheel paths, the surface was smooth to the touch. The surface smoothness became less pronounced as the deck was traversed east to west. At the approach guard angle, material had been removed down to the original deck surface over the first two inches of deck length. Surface delaminations, as large as 2.5 inches in diameter, were seen. The majority of these delaminations were located along the construction seam between the passing and driving lanes (see Figure 5.1.1, Photo 21). A number of gouges, apparently from snow plowing, were present. No cracks were seen on the westbound structure. The patched construction delamination (in the westbound driving lane, see Section 3.1.1) appeared to be holding.

The eastbound Gallatin structure exhibited many of the same distresses as the westbound structure. Wheel paths, evident in the eastbound driving lane, exhibited a similar smoothness to the touch when compared to the westbound Gallatin Bridge. The delaminations at the approach guard angle, first observed 2 days after traffic reintroduction, had not changed substantially over the intervening year. Delaminations, similar in size to those on the westbound lanes, were seen. The seam between the driving and passing lanes had a nearly continuous delamination. Marring from snow plows was observed. No cracking was seen on this structure.

Table 5.0.1: Summary of Visually Observed Distress, First Annual Evaluation (after one winter of service)

Overlay	Age at Time of Observation (months)	Description of Visually Observed Distress			
		General Wear	Delaminations	Cracking	Other
Thorotop HCR					
Gallatin	12	Obvious wear in the wheel paths, with surface smooth to the touch	Several, as large as 2.5 inches in dia.	None	
West Garrison	10	Same as Gallatin	Several	None	
Silica Fume					
Galen	7	None	None	None	
Flexolith					
Madison	11	Wheel paths evident, surface still rough in these paths, but smoother than rest of deck	None	Some reflective cracking	All seams clearly visible
East Garrison	11	Same as Madison	None	None	Same as Madison
Degadur					
Fairmont	10	Surfaces generally smooth to touch, attributed to seal coat; popouts occurring	Few, roughly 4 to 6 inches in dia.	Single crack, WB	
Bozeman	12	Not Available	Not Available	Not Available	

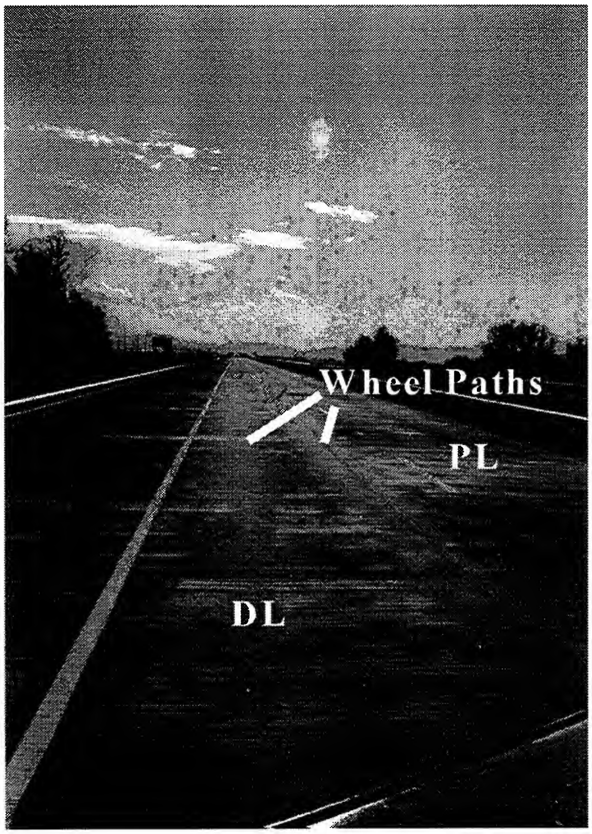


Photo 20: Gallatin westbound, looking east.

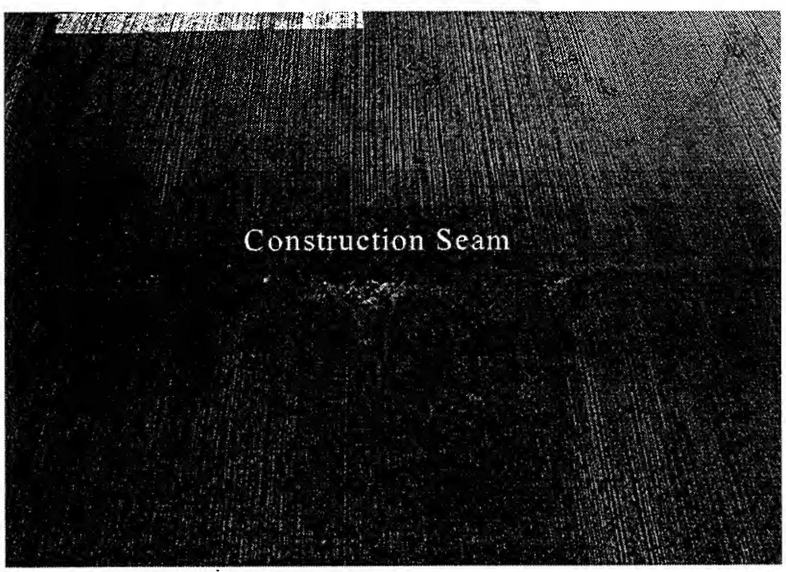


Photo 21: Gallatin, surface condition.

Figure 5.1.1: Gallatin Photographs, Thorotop HCR, First Annual Evaluation.

Figure 5.1.2 shows the condition of the Thorotop HCR structures at the West Garrison Interchange at the time of their first annual evaluation. Many of the distresses noted for the Gallatin bridges were also observed on these structures. Wheel paths were evident in the driving lanes. The pattern of smoothness observed in the wheel paths was similar to that of the Gallatin bridges. A number of delaminations were noticed at the expansion and construction joints. Additional delaminations were seen on the shoulders and on the driving surface on the westbound structure. Further analysis of the delamination locations revealed no correlation with pre-installation distresses. Marring from snow plow activity was seen. No cracking was observed on these bridges.

Photo 22: West Garrison, westbound.

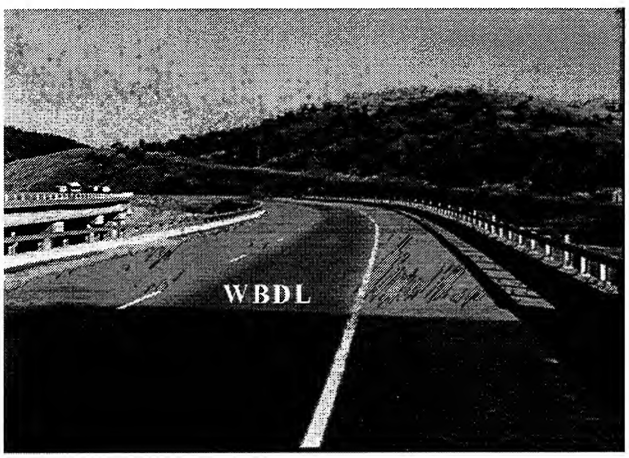


Photo 23: West Garrison, westbound.

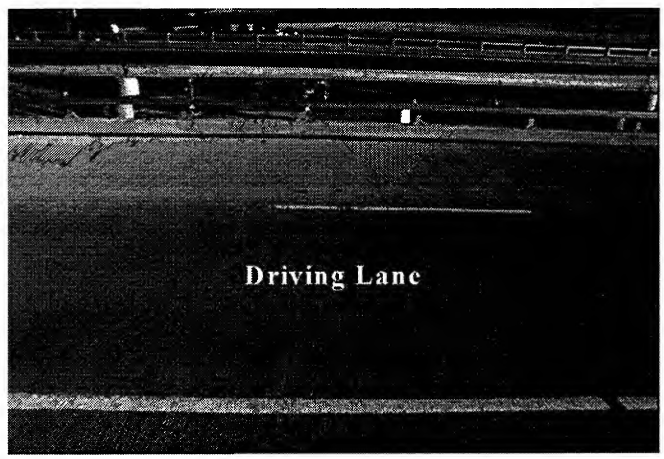


Photo 24: West Garrison, delamination.

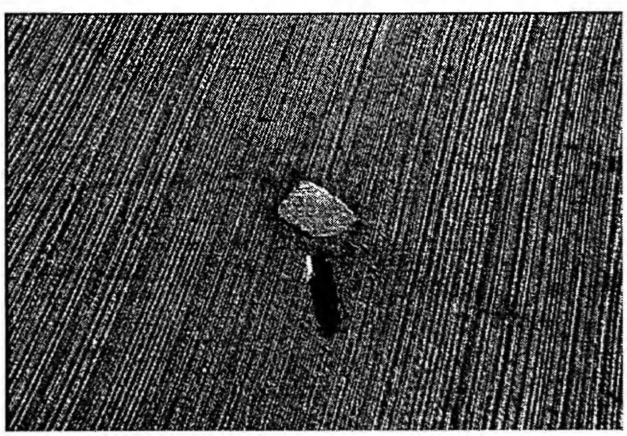


Figure 5.1.2: West Garrison Photographs, Thorotop HCR, First Annual Evaluation.

5.1.2 Silica Fume

The annual evaluation of the silica fume bridges at the Galen Interchange was performed on March 21, 1997. Minimal change was noticed on these decks relative to their initial post-construction conditions. No distresses were seen on either structure.

5.1.3 Flexolith 216

The first of the Flexolith 216 bridges evaluated was the westbound bridge at the Madison River near Three Forks (see Figure 5.1.3). As had been the case with all of the Thorotop HCR bridges, wheel paths were visible in the driving lanes, and the surface of the deck was smoother in these areas compared to the rest of the structure. This smoothness appeared to result from the loss of surface aggregate in the wheel paths. None the less, the Flexolith 216 wheel paths were noticeably rougher to the touch than the Thorotop HCR wheel paths. Areas where the aggregate coverage appeared inadequate at the completion of construction were conspicuous after one year. All construction seams were visible. Some reflective cracking could be seen above two of the bents in the driving lanes. An oval shaped crack, 12 inches by 18 inches, was found on the west end of the passing lane (see Figure 5.1.3, Photo 26). Surface marring, perhaps from snowplowing, was also seen. This marring was less extensive and less severe than was observed on the Thorotop overlays.

Photo 25: Madison, westbound.

Photo 26: Madison River, oval crack.

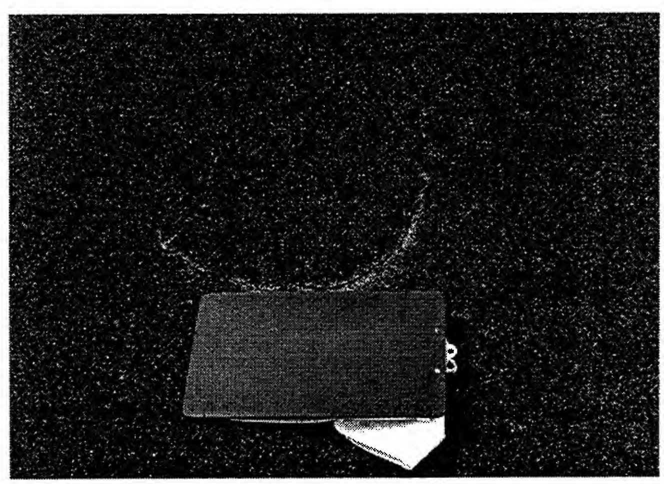


Figure 5.1.3: Madison Photographs, Flexolith 216, First Annual Evaluation.

The eastbound bridge at the Madison River exhibited many of the same distresses as were observed on the westbound bridge. Wheel paths were distinctly visible in the driving lane, and the surface was smoother in these paths than on the rest of the bridge. Loss of surface aggregate again appeared to be responsible for this condition. Reflective cracking was seen above three of the bents. No other cracking was found. All construction seams were distinctly visible. A similar amount of snow plow marring had occurred on this bridge as had been seen on the westbound bridge.

The westbound and eastbound East Garrison bridges had many of the same distresses as had been seen on the Madison bridges. Removal of aggregate in the wheel paths once again resulted in a visibly smoother surface in these areas. A minimal amount of snow plow marring had occurred on both structures. No cracking was seen. Figure 5.1.4 further documents the condition of the East Garrison bridges.

Photo 27: East Garrison, eastbound.

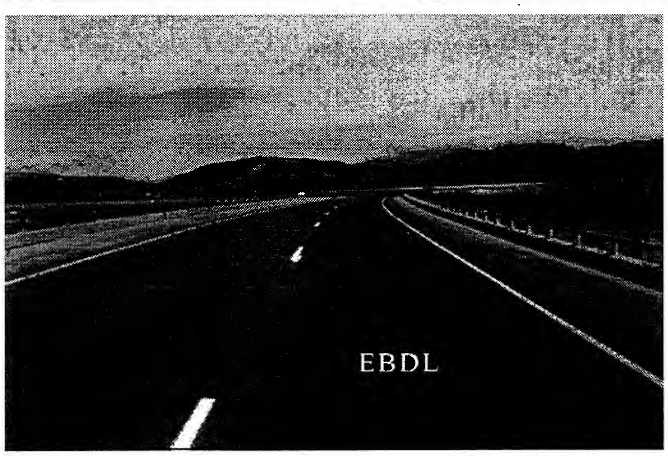


Photo 28: East Garrison, eastbound.

Figure 5.1.4: East Garrison Photographs, Flexolith 216, First Annual Evaluation.

5.1.4 Degadur 330BD

The only structures evaluated in 1996 that had received a Degadur MMA overlay treatment were those near the Fairmont Interchange. Both of the eastbound and westbound structures at Fairmont were performing in a similar fashion. While wheel paths were evident in the driving lanes, from general wear, the surfaces of the bridges were uniformly smooth to the touch across the entire structure. This condition appeared to be a result of the seal coat more so than poor aggregate coverage or removal. Popouts, as described in SHRP-P-338 (*15*), were noted on the surface of the overlays of both decks. Delaminations were found on both structures. Three delaminations were located on the westbound bridge; only one, on the eastbound bridge. While the sizes of these delaminations were not measured due to the high volume of traffic at the time of the evaluation, these areas were roughly 4 to 6 inches in diameter. The only crack found was on the westbound deck. It extended through the entire depth of the overlay at the approach guard angle.

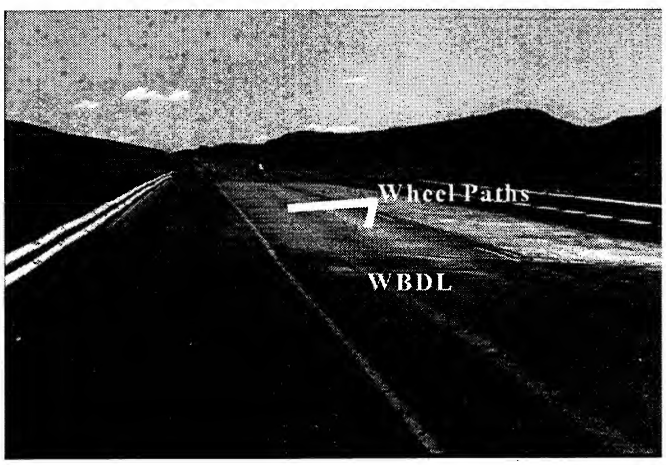


Photo 29: Fairmont - westbound.

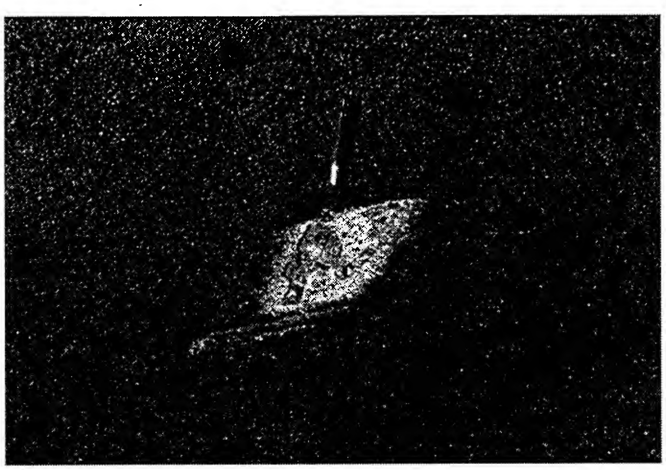


Photo 30: Fairmont Delamination.

Figure 5.1.5: Fairmont Photographs, Degadur MMA, First Annual Evaluation.

6. INTERIM EXAMINATION

6.0 GENERAL REMARKS

Examinations of the Thorotop HCR, Flexolith 216, and Degadur 330BD overlays were made after their second winter of service (immediately before the end of this project). These examinations were made March 21 and 28, 1997. Table 6.0.1 summarizes observations from the interim examination. These observations provided some indication of the continuing deterioration of the overlays with use.

6.1 OVERLAY TECHNOLOGIES

6.1.1 Thorotop HCR

Two distinctly different wearing patterns were evident for the Thorotop HCR overlays after 2 winters of service. The overlays at the West Garrison Interchange displayed transverse and alligator cracking. In other respects, however, they appeared very similar to their condition at the end of their first year of service (see Figure 6.1.1). At the Gallatin bridges, the overlay was worn off in high traffic areas. The original deck surface of the Gallatin structures was clearly visible in the wheel paths of the driving lanes (see Figure 6.1.1). The difference in performance between the West Garrison and Gallatin structures is consistent with the observations of overlay thickness that were made during the adhesion testing of these decks. Based on the cores produced by the adhesion tests, the Thorotop overlay at the Gallatin was much thinner than the overlay at West Garrison (less than 1/16-inch thick compared to 1/8 to 1/4-inch thick, respectively). Reflective cracking, both transverse and alligator, was very pronounced at the Gallatin. Snow plow marring increased on all of the overlaid bridges compared to that observed in the first annual evaluation.

For the 5-year period prior to the installation of the Thorotop HCR overlay, the accident rate averaged 2 per year with a maximum of 3 per year (*16*). In the 14 months since the installation of the overlay, 13 accidents occurred, yielding an accident rate of 11 per year. These accidents have occurred under icy conditions in the months of October and November. During this 2-month period

Table 6.0.1: Changes in Visually Observed Distress After Two Winters of Service.

Overlay	Age at Time of Observation (months)	Description of Visually Observed Distress			
		General Wear	Delaminations	Cracking	Other
Thorotop HCR					
Gallatin	19	Overlay worn off in the wheel paths, original deck clearly exposed	Unchanged since annual evaluation	Pronounced reflective transverse and alligator	
West Garrison	17	Unchanged since first annual evaluation	Unchanged since annual evaluation	Reflective transverse and alligator	
Silica Fume					
Galen	-	Not available	Not available	Not available	Overlay only one year old
Flexolith					
Madison	18	Unchanged since first annual evaluation	None	Some reflective and alligator cracking	
East Garrison	18	Same as Madison	One	Some reflective cracking	
Degadur					
Fairmont	17	Generally unchanged since first annual evaluation, surface nominally smoother than at first annual evaluation	Unchanged since annual evaluation	Unchanged since annual evaluation	
Bozeman	19	Conditions appear similar to the Fairmont bridge	None	Numerous	

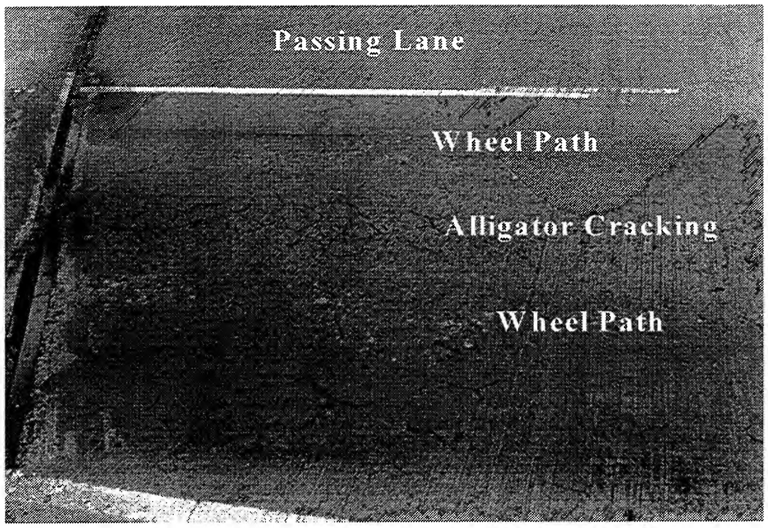


Photo 31: Gallatin, typical driving surface.

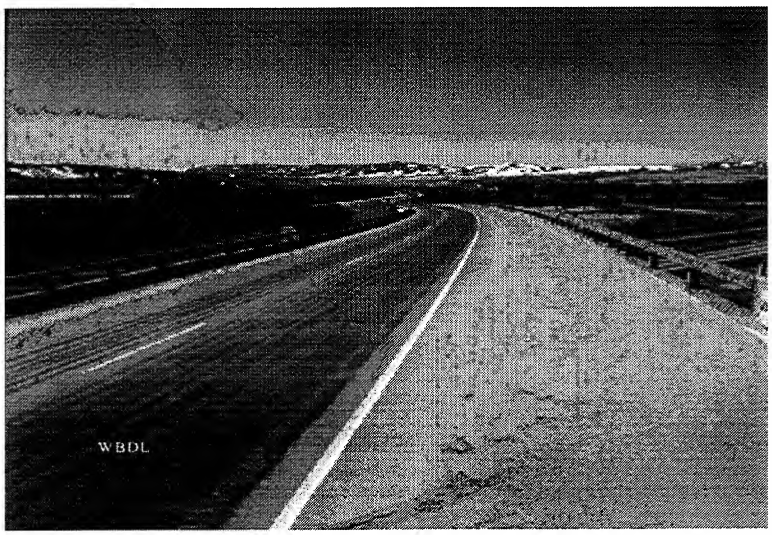


Photo 32: West Garrison, westbound.

Figure 6.1.1: Thorotop HCR, Interim Evaluation (after two winters of service).

in the first year following installation of the overlay, 4 accidents occurred. In October and November of the second year after overlay installation, 9 accidents occurred. Neither increases in traffic nor the occurrence of unusual environmental conditions appeared to be responsible for the increase in accidents at this location. The geometry at West Garrison includes a 2° 30' horizontal curve and a 7 percent superelevation. Note that the generally recommended maximum superelevation is 8 percent (*17*). This geometry requires high skid resistance to insure adequate safety. The Thorotop HCR installations at the Gallatin have not experienced the same increase in

accidents rates observed at West Garrison. These bridges, however, are short in length and straight in alignment. In this situation, the skid resistance of the deck is less crucial to safe vehicle performance.

6.1.2 Flexolith 216

The condition of the decks overlaid with Flexolith 216 did not change significantly over their second winter of use. Loss of aggregate, which had primarily been occurring in the wheel paths, appeared to have ceased. Reflective cracks did develop over all of the bents on all of the bridges. A delamination occurred at the expansion joint near the approach of the eastbound East Garrison bridge. An area of alligator cracking developed on the westbound driving lane of the Madison bridge. This area is located at the east end of the bridge on a high spot in the overlay material. This high spot may have been routinely struck by snow plows. Marring from snow plows has not changed appreciably since the first annual evaluation. The oval crack found in the first annual evaluation on the westbound passing lane did not seem to have changed in extent or severity.

6.1.3 Degadur 330BD

The condition of the Fairmont structures did not change significantly over their second winter of service. No new delaminations or cracks appeared. Surface marring from snow plows remained nearly constant. The surface of the overlays appeared to be smoother than was observed in the first annual evaluation. Skid testing this summer (1997) will verify or refute this observation.

The MMA material installed on the 19th Street Interchange generally appeared to be in good condition. Problems may be developing in the overlay, however, that originate in the underlying concrete deck. Transverse cracks were observed on the underside of the deck at 5-10 foot intervals along the length. These cracks appeared to extend through the entire thickness of the deck and were reflected in the Degadur MMA overlay.

7. CONCLUSIONS

The objective of this project is to determine the engineering performance and life cycle costs associated with using thin bonded overlays in rehabilitating concrete bridge decks. To pursue these objectives, MDT received a 2-year contract with FHWA to install and monitor the performance of four different overlay materials on a total of 13 bridges at 7 locations on Interstate 90 in southwestern Montana. Three overlay materials, Thorotop HCR (polymer concrete), Flexolith 216 (epoxy/aggregate system), and MMA (resin/aggregate system) were put down in the 1995 construction season; the fourth overlay material, silica fume concrete, was placed in the 1996 construction season. While documentation has been completed on the installation, the initial performance, and the initial costs of each deck treatment, not enough time has gone by (less than two years on the Thorotop HCR, Flexolith 216, and Degadur 330BD, and less than one year on the silica fume concrete) to confidently predict and compare life cycle performance and cost. The data collected to-date, however, do support some conclusions on relative overlay performance.

The most crucial early observation is the poor performance of Thorotop HCR. Further study and use of this material may be unwarranted, based upon an examination of the data collected to-date on its performance. The skid numbers acquired in 1996 were lowest on the Thorotop bridges. While these numbers possibly were acceptable in the summer when taken at warm temperatures, the performance under more adverse conditions is unacceptable, as reflected in the increase in accidents on one set of Thorotop structures (West Garrison) since the installation of the overlay. Based on Thorotop HCR performance at West Garrison, it may not offer adequate skid resistance at low temperature, or it may be prone to icing. As a result of MDT's internal investigation of the accident situation at West Garrison (***16***), they have removed the Thorotop overlay and installed a high molecular weight methacrylate. While the second set of bridges overlaid with Thorotop HCR (Gallatin) have not experienced an increase in accident rates, the overlays have worn to the point that the original surfaces of the decks are now visible in the wheel paths of the driving lanes. Therefore, despite the low initial cost for the Thorotop HCR overlays relative to the other treatments ($22.00 verse approximately $40.00/yd^2), this treatment may have the highest life cycle costs.

The remaining overlay treatments, silica fume concrete, Flexolith 216, and Degadur 330BD, are thus far providing acceptable service, and durability has not yet become an issue with any of

these treatments. Winter time skid resistance on these overlays appears to be adequate. This conclusion is reinforced for Flexolith 216 by its performance at one of the demonstration installations (East Garrison). While conditions at this structure are comparable to those at the problematic Thorotop installation close by, the accident rate has not increased as observed for the Thorotop HCR.

The initial costs of these treatments are similar in magnitude, ranging from \$36 to \$44/yd^2 (excluding the Thorotop HCR). With the exception of the Thorotop HCR treatment, life cycle costs of the various overlays cannot be reasonably estimated at this time. Insufficient deterioration has occurred for the silica fume concrete, Flexolith 216, and Degadur 330BD overlays to permit reliable extrapolation of their service lives.

8. RECOMMENDATIONS & IMPLEMENTATION

It is recommended that this contract be extended to at least September 30, 2001 so that the long term performance data necessary for the formulation of meaningful comparisons between the cost and performance of each deck treatment can be collected. Sufficient trends in overlay performance may have emerged after 5 years of use to permit the extrapolation of design lives and the subsequent comparison of the predicted life cycle costs for each treatment. It is further recommended that MDT continue to monitor overlay performance beyond this 5-year period, perhaps at 5-year intervals, until each overlay life is reached.

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APPENDIX A

Presented in this appendix are pre-installation information and distress maps prepared for each deck prior to any repair activities:

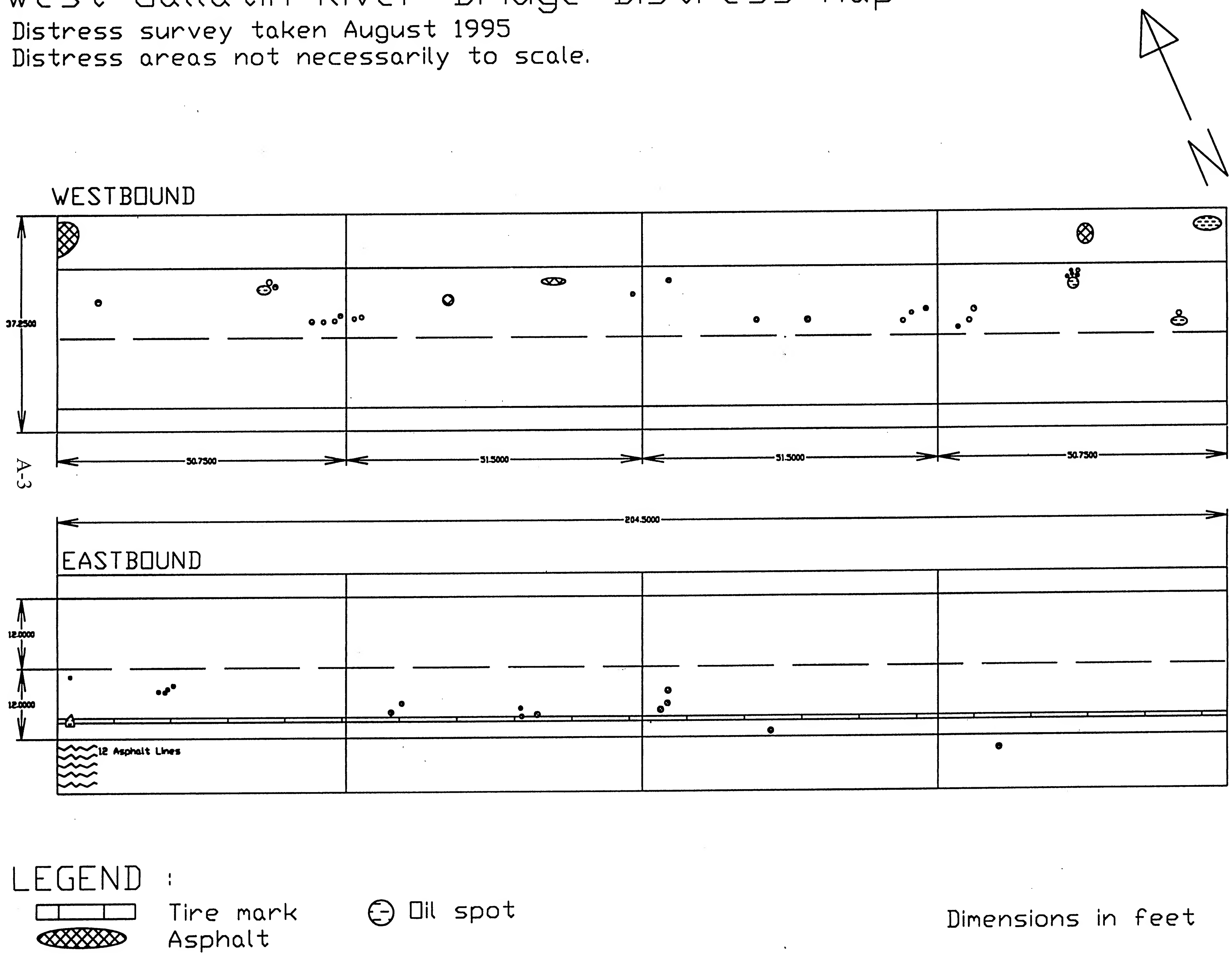
Table A-1: Pre-Installation Information.

Material	Location	% Area Below -0.20 V CSE*	% Area Above -0.35 V CSE	Average Chloride Content (lb/yd^3)	Delamination Area (ft^2) (Delam./Total Area)
Thorotop HCR					
	EB Gallatin	N/A**	N/A	0.05	112/7423
	WB Gallatin	N/A	N/A	0.26	127/7628
	EB W. Garrison	65.7	0.4	0.28	49/24789
	WB W. Garrison	93.2	0.3	0.30	115/24250
Silica Fume					
	EB Galen	62.0	1.7	0.46	433/5582
	WB Galen	71.7	5.6	0.37	246/5582
Flexolith 216					
	EB Madison	N/A	N/A	0.20	1165/20580
	WB Madison	N/A	N/A	0.25	474/17458
	EB E. Garrison	89.4	0.0	0.46	13/28350
	WB E. Garrison	98.2	0.0	0.14	1/29820
Degadur MMA					
	EB Fairmont	N/A	N/A	0.15	0/8018
	WB Fairmont	N/A	N/A	0.16	0/8018
	S. Nineteenth	N/A	N/A	N/A	N/A

*CSE - Copper Sulfate Electrode
**N/A - Not Available

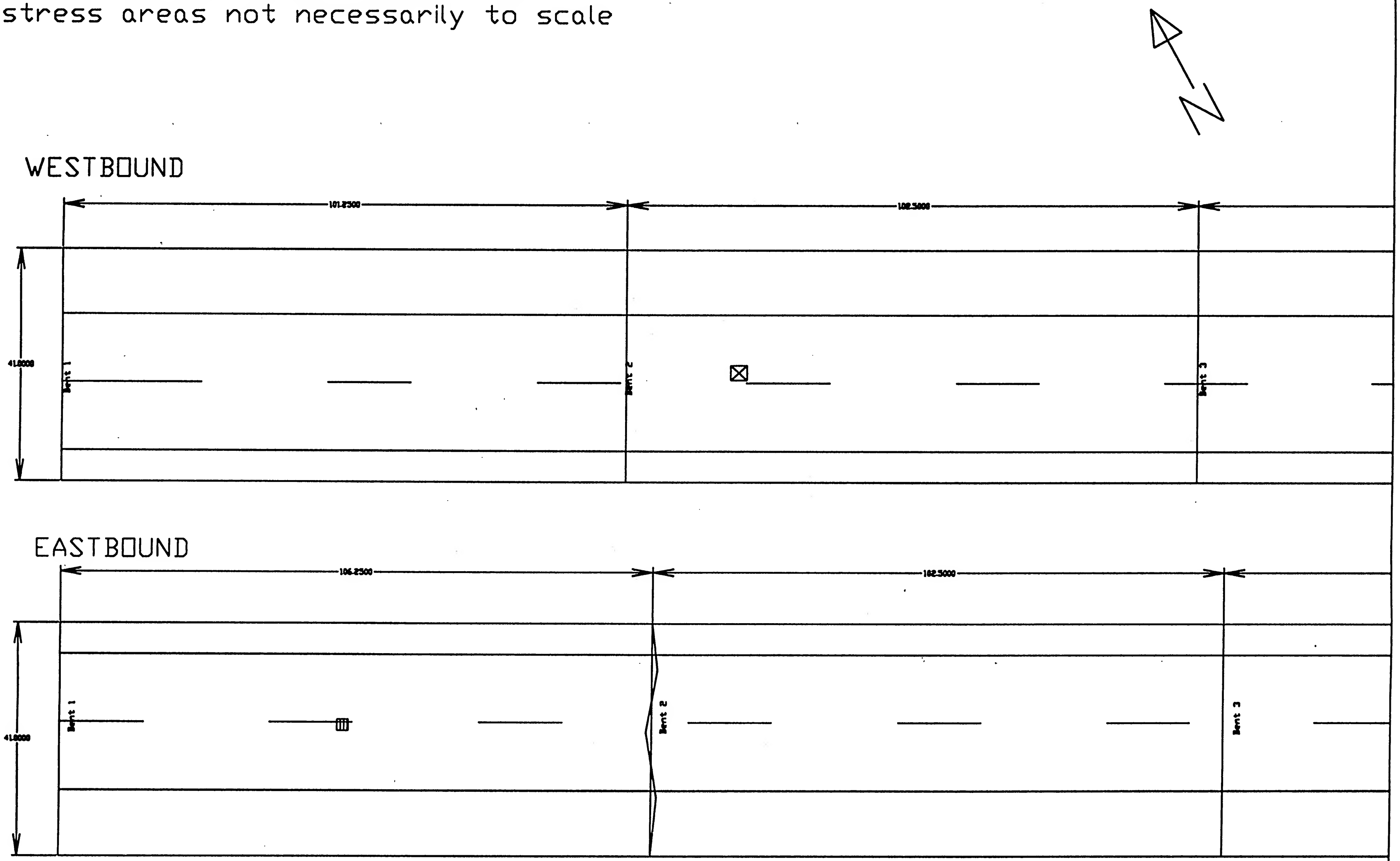
West Gallatin River Bridge Distress Map

Distress survey taken August 1995
Distress areas not necessarily to scale.



West Garrison Bridge Distress Map

Distress survey taken October 1995
Distress areas not necessarily to scale



LEGEND:

Holes

Transverse cracks

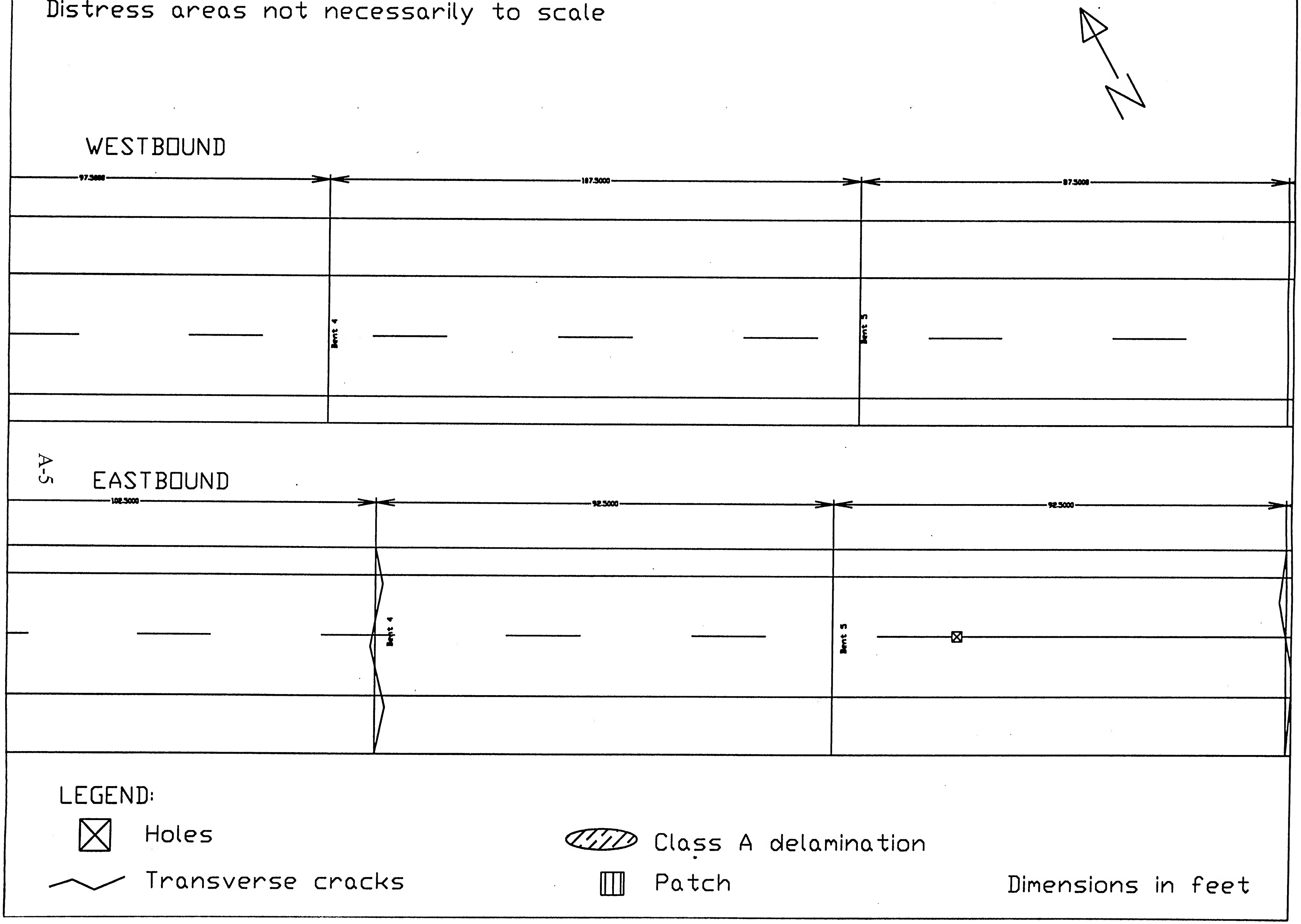
Class A delamination

Patch

Dimensions in feet

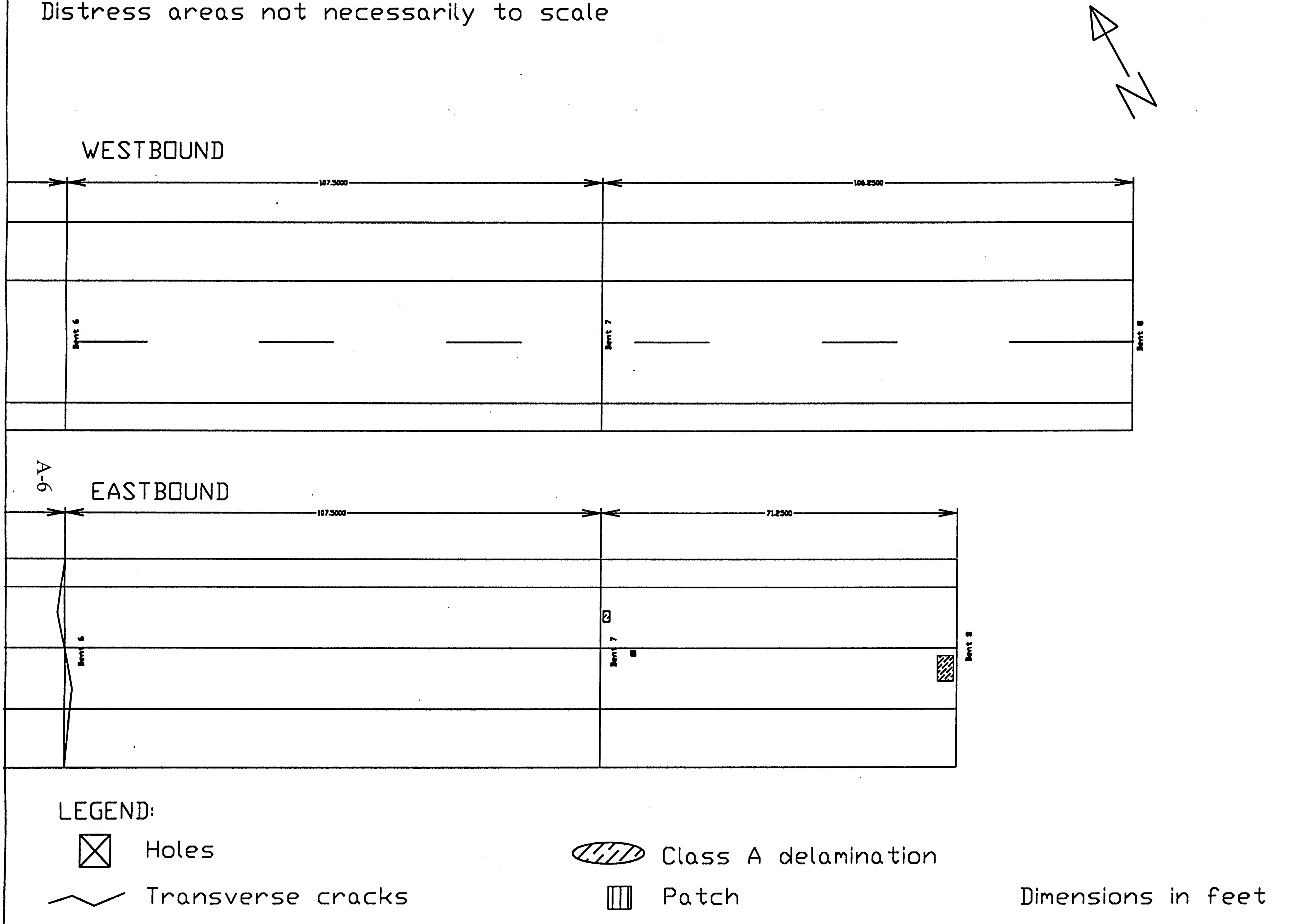
West Garrison Bridge Distress Map

Distress survey taken October 1995
Distress areas not necessarily to scale



West Garrison Bridge Distress Map

Distress survey taken October 1995
Distress areas not necessarily to scale



Galen Bridge Distress Map

Distress survey taken : July 1996

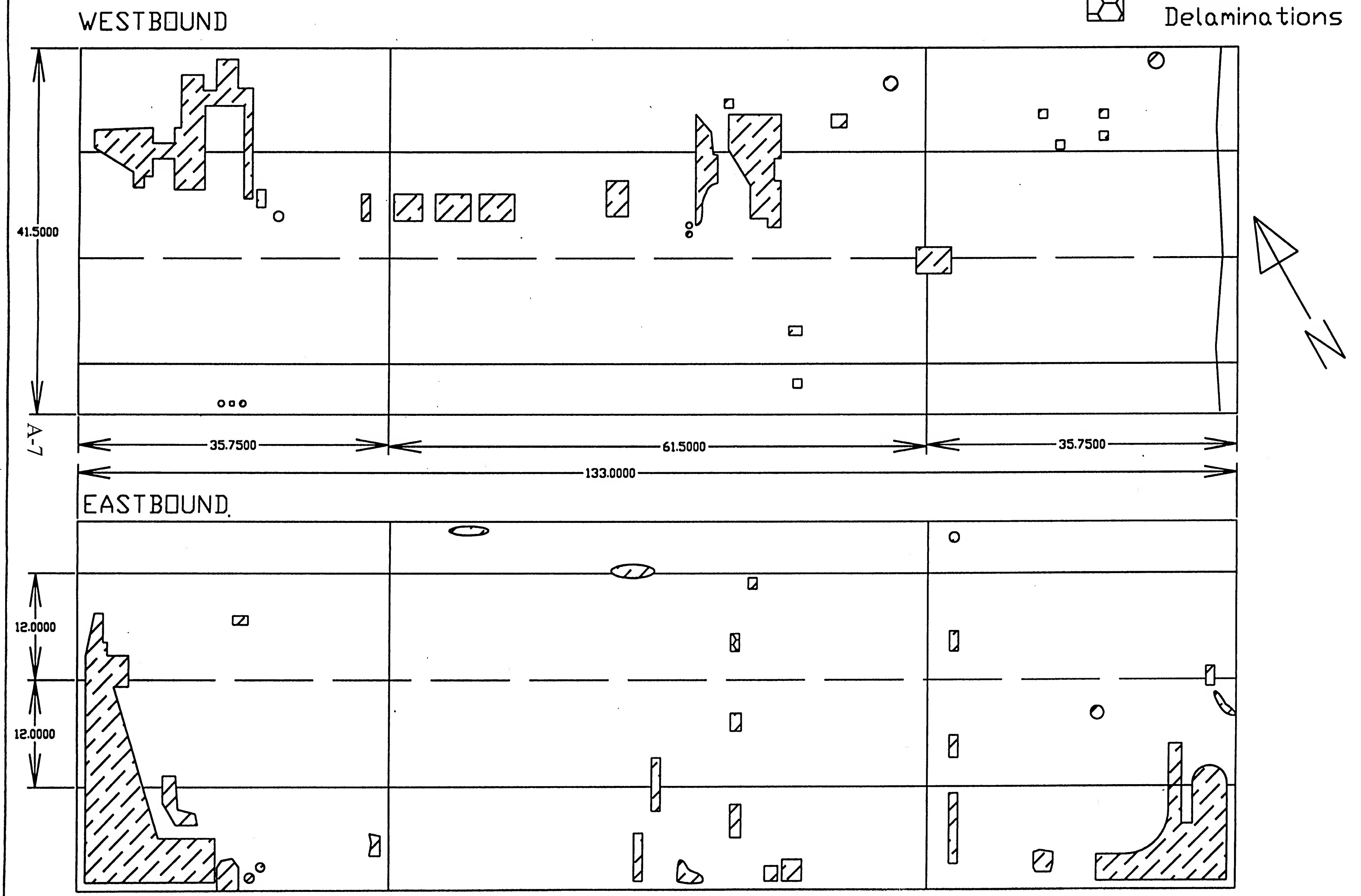
Distress areas not necessarily to scale.

Dimensions in feet

Legend :

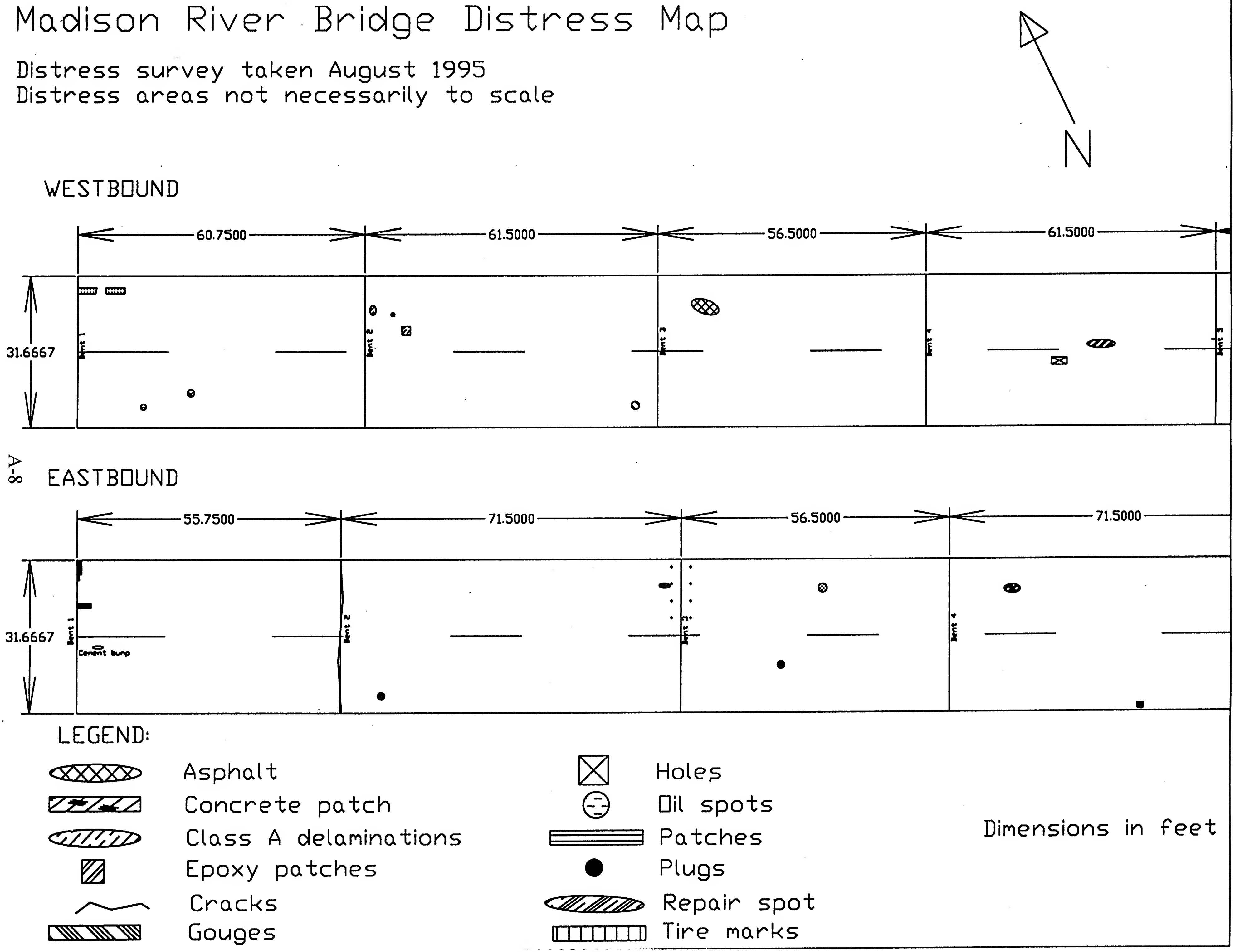
Class A Delaminations

Class B Delaminations



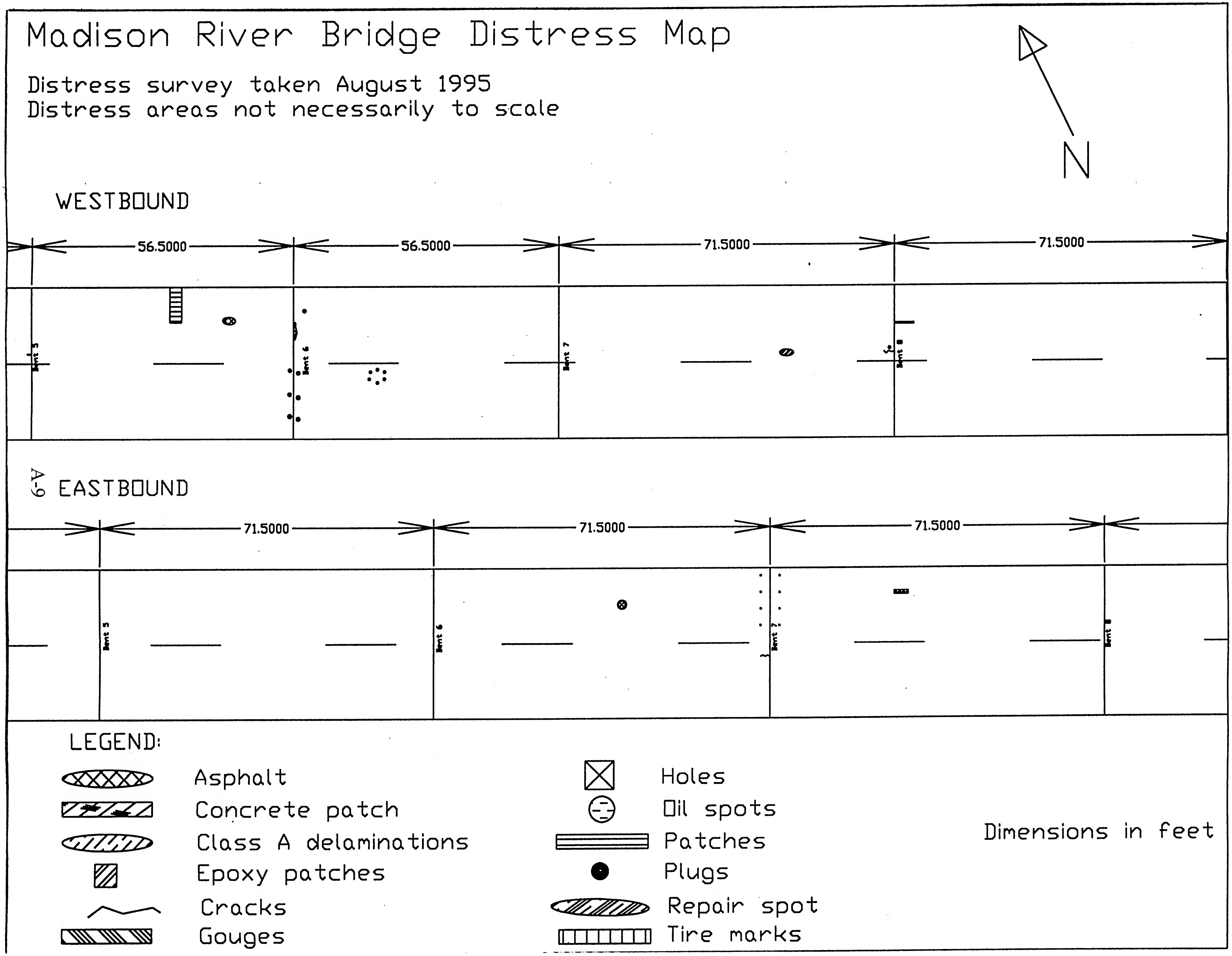
Madison River Bridge Distress Map

Distress survey taken August 1995
Distress areas not necessarily to scale



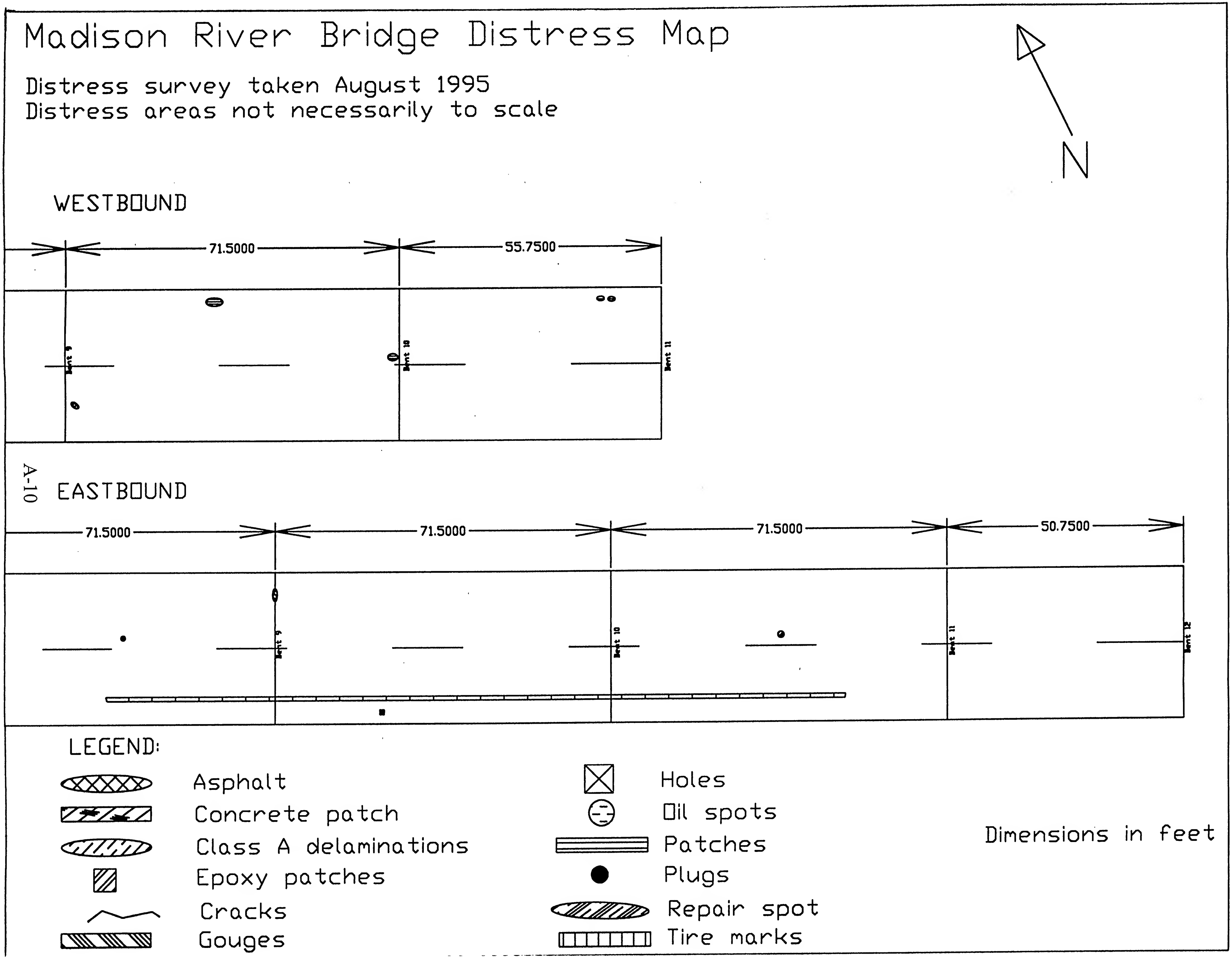
Madison River Bridge Distress Map

Distress survey taken August 1995
Distress areas not necessarily to scale



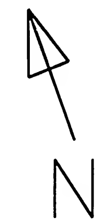
Madison River Bridge Distress Map

Distress survey taken August 1995
Distress areas not necessarily to scale

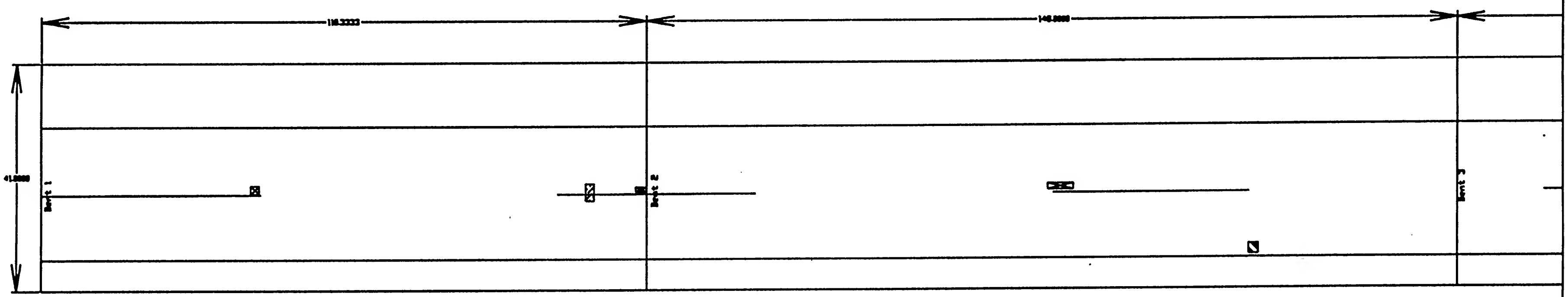


East Garrison Bridge Distress Survey

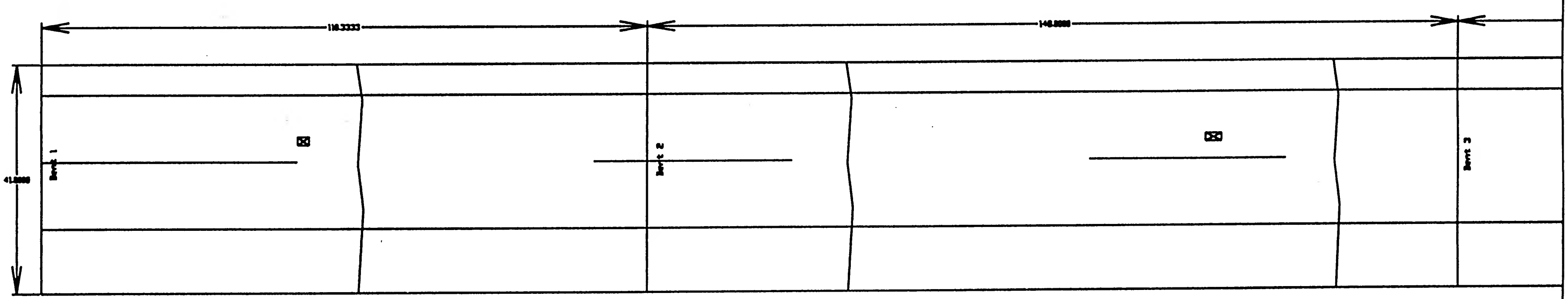
Distress survey taken September 1995
Distresses not necessarily to scale



WESTBOUND



EASTBOUND

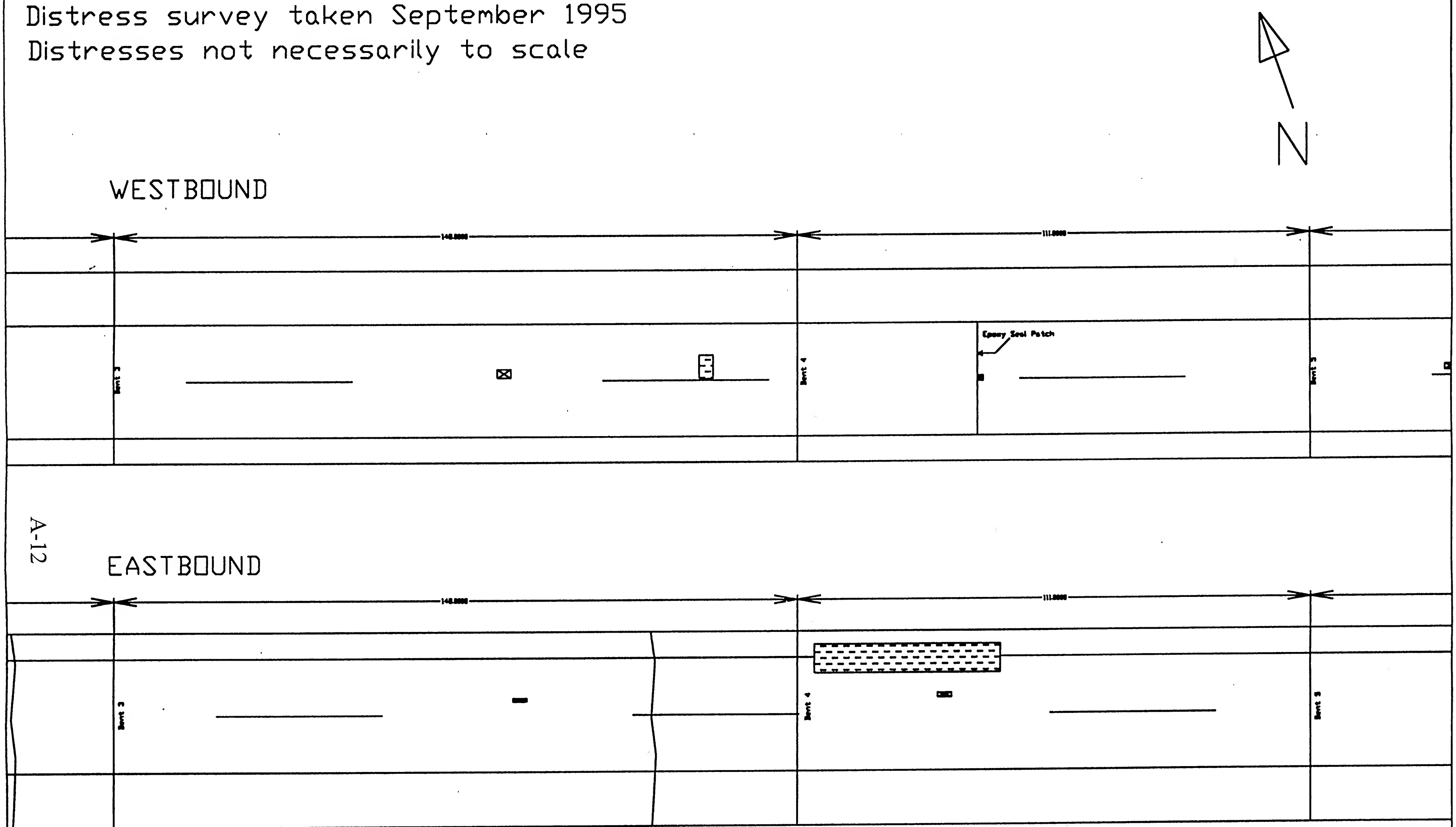


LEGEND :

Dimensions in feet

East Garrison Bridge Distress Survey

Distress survey taken September 1995
Distresses not necessarily to scale



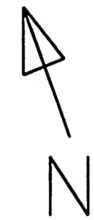
LEGEND :

- Holes
- Class A delaminations
- Epoxy Patch
- Transverse Cracks
- Oil Spots

Dimensions in feet

East Garrison Bridge Distress Survey

Distress survey taken September 1995
Distresses not necessarily to scale



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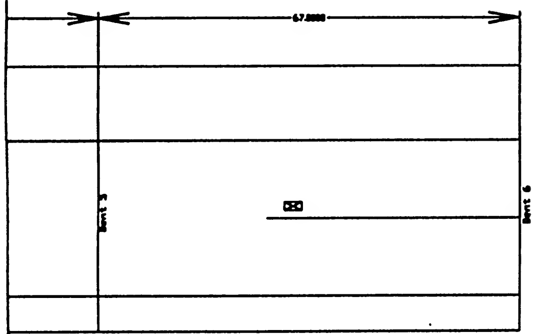
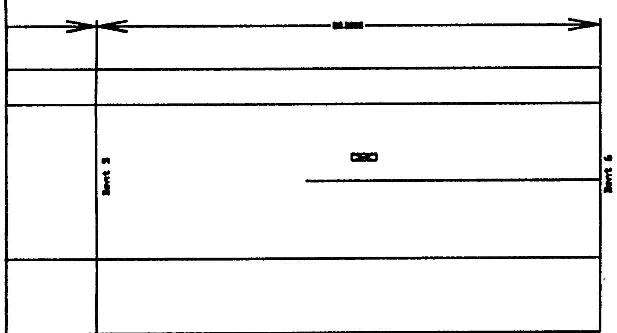


EASTBOUND



LEGEND :

Holes
Class A delaminations
Epoxy Patch

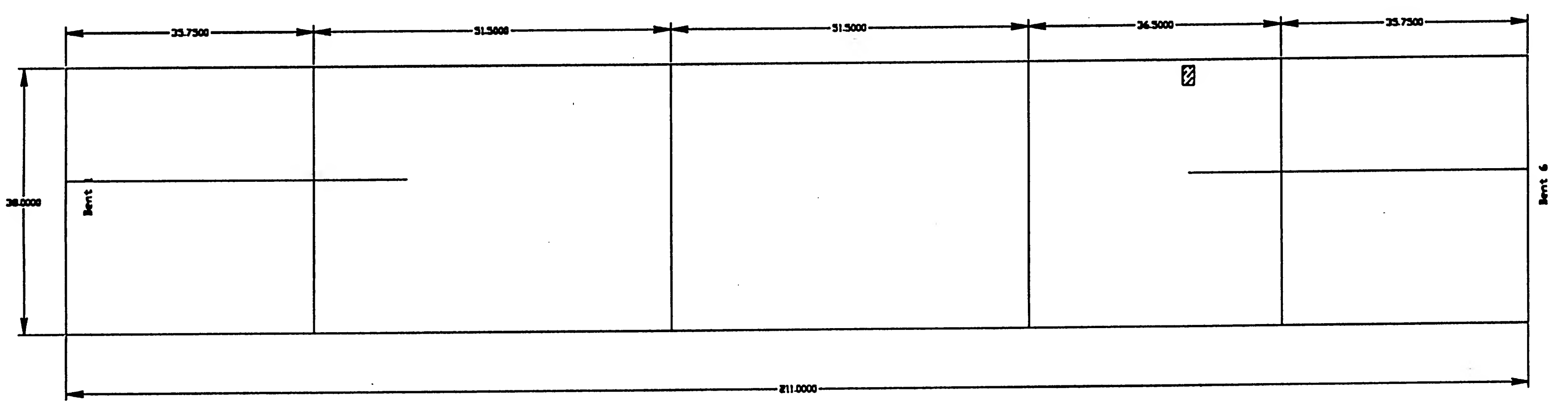
Transverse Cracks
Oil Spots

Dimensions in feet

MP 210 Bridge (over railroad) Distress Map

Distress survey taken September 1995
Distress areas not necessarily to scale

WESTBOUND



No distresses found for EASTBOUND lanes

LEGEND:

Class A delaminations

Dimensions in feet

APPENDIX B

This appendix contains quantative information related to the installation and performance of each overlay. The information is organized by activity and treatment type:

Table B-1: Placement Information - Thorotop HCR

Lift*	**Starting Temperature** (Ambient/Deck)	**Ending Temperature**** (Ambient/Deck)	**Relative Humidity** (Percent)	**Placement Time** (Minutes)	**Traffic Reintroduction** (Days after overlay completed)
Gallatin					
1st EBDL	61°F/67°F	75°F/82°F	35.6	80	
2nd EBDL	67°F/67°F	-	35.6	100	2
1st WBDL	62°F/55°F	-	33.0	80	
2nd WBDL	69°F/71°F	-	33.0	60	3
1st EBPL	77°F/87°F	-	39.0	50	
2nd EBPL	80°F/85°F	-	39.0	60	4
1st WBPL	82°F/87°F	-	16.3	95	
2nd WBPL	88°F/95°F	-	16.3	80	3
West Garrison					
1st WBDL (0 - 60 ft.)	54°F/54°F	-	N/A***	N/A	
2nd WBDL (0 - 60 ft.) 1st WBDL (+60 ft.)	59°F/57°F	72°F/77°F	25.8	335	
2nd WBDL (60 - 210 ft.)	78°F/80°F	67°F/67°F	25.8	145	
2nd WBDL (+210 ft.)	51°F/50°F	67°F/68°F	25.1	255	7
1st EBDL (0 - 500 ft.)	49°F/49°F	-	54.0	190	
2nd EBDL (0 - 500 ft.)	56°F/60°F	-	54.0	190	
1st EBDL (+500 ft.)	40°F/45°F	-	36.7	100	
2nd EBDL (+500 ft.)	54°F/54°F	-	36.7	70	4
1st WBPL	55°F/57°F	-	41.4	155	
2nd WBPL (0 - 235 ft.)	62°F/62°F	56°F/56°F	41.4	135	
2nd WBPL (+235 ft.)	50°F/50°F	61°F/61°F	41.4	65	5
1st EBPL (0 - 210 ft.)	64°F/64°F	-	20.5	85	
2nd EBPL (0 - 210 ft.)	77°F/79°F	-	20.5	85	
1st EBPL (+210 ft.)	76°F/76°F	-	20.5	85	
2nd EBPL (+210 ft.)	69°F/69°F	-	20.5	80	4

*EBDL - Eastbound Driving Lane; WBDL - Westbound Driving Lane; EBPL - Eastbound Passing Lane; WBPL - Westbound Passing Lane.
**Recorded only if temperatures changed from the starting temperatures.
***N/A - Not Available.

Table B-2: Silica Fume Placement Data

Lift	**Temperature** (Ambient/Deck)	**Wind Speed**	**Relative Humidity**	**Placement Time**	**Traffic Reintroduction** (Days after overlay completed)
Westbound	50°F/51°F (start)	1.2-3.4 mph	30-70%	260 Minutes	6
Eastbound	76°F/75°F (start) 58°F/60°F (finish)	0.3-4.0 mph	33-60%	225 Minutes	6

Table B-3: Placement Information Degadur MMA (Fairmont only)

Lift	**Starting Temperature** (Ambient/Deck)	**Ending Temperature*** (Ambient/Deck)	**Relative Humidity** (Percent)	**Placement Time** (Minutes)	**Traffic Reintroduction** (Days after overlay completed)**
WBPL Primer	70°F/ 74°F	70°F/ 74°F	25.1	70	
EBPL Primer	66°F/ 66°F	-	25.1	65	
WBPL Base	60°F/61°F	-	38.4	270	
WBPL Seal	N/A***	N/A	38.4	N/A	
EBPL Base	52°F/53°F	69°F/69°F	31.6	205	
EBPL Seal	68°F/71°F	-	31.6	75	
WBDL Primer	69°F/69°F	-	31.6	65	
WBDL Base	41°F/42°F	57°F/60°F	64.1	260	
WBDL Seal	N/A	60°F/63°F	64.1	50	
EBDL Primer	40°F/41°F	-	60.9	100	
EBDL Base	47°F/47°F	49°F/49°F	60.9	220	
EBDL Seal	49°F/49°F	-	60.9	N/A	

*Recorded only if temperatures changed from the starting temperatures.
**Traffic can be reintroduced to MMA nightly during the construction process.
***N/A - Not Available.

Table B-4: Placement Information - Flexolith 216

Lift*	**Starting Temperature** (Ambient/Deck)	**Relative Humidity** (Percent)	**Placement Time** (Minutes)	**Traffic Reintroduction** (Hours after overlay completed)
Madison River				
1st Left ½ (-325 Ft.) WBDL	75°F/80°F	39.0	160	
2nd Left ½ (-325 Ft.) WBDL	92°F/102°F	39.0	110	
1st +325 Ft. WBDL	60°F/65°F	45.6	110	
1st Right ½ (-325 Ft.) WBDL	60°F/65°F	45.6	50	
2nd Right ½ (-325 Ft.) WBDL	48°F/49°F	24.1	235	
2nd +325 Ft. WBDL	48°F/49°F	24.1	Total	23
1st -370 Ft. EBDL	85°F/96°F	24.1	110	
2nd -100 Ft. EBDL	89°F/96°F	24.1	60	
2nd 100-370 Ft. EBDL	64°F/62°F	10.9	125	
1st +370 Ft. EBDL	64°F/62°F	10.9	75	
2nd +370 Ft. EBDL	87°F/94°F	10.9	140	72
1st & 2nd WBPL	Appx. 74°F	25.3	N/A**	48
1st EBPL	85°F/92°F	25.3	120	
2nd EBPL	N/A	N/A	N/A	>48
East Garrison				
1st WBDL	75°F/ 78°F	47.3	70	
2nd WBDL (+205 Ft.)	75°F/ 78°F	47.3	115	
2nd WBDL (-205 Ft.)	65°F/67°F	45.5	85	<24
1st EBDL	56°F/72°F	38.4	155	
2nd EBDL	N/A	38.4	285	<18
1st WBPL	78°F/79°F	32.7	160	
2nd WBPL	59°F/60°F	43.7	340	<24
1st EBPL	80°F/85°F	43.7	95	
2nd EBPL	61°F/67°F	31.0	315	<24

*EBDL - Eastbound Driving Lane; WBDL - Westbound Driving Lane; EBPL - Eastbound Passing Lane; WBPL - Westbound Passing Lane.
**N/A - Not Available

Table B-5: Adhesion Results - Thorotop HCR

Location	Failure by Type					Average Pounds Pull	Average psi	Overlay Thickness	Age at time of test
	1	2	3	4	5				
WB Gallatin	4					781	249	<1/16 inch	15 months
WB Gallatin	4					613	223	<1/16 inch	15 months
EB Gallatin	4					750	239	<1/16 inch	15 months
EB Gallatin	4					894	285	<1/16 inch	15 months
WB West Garrison	3		1			756	241	1/8 - 3/16 inch	10 months
WB West Garrison	1		1		1	275	88	1/8 inch	10 months
WB West Garrison	1		2		1	588	187	1/4 inch	10 months
EB West Garrison				4		623	211	N/A*	10 months
EB West Garrison				4		756	421	N/A	10 months
EB West Garrison				4		488	151	N/A	10 months

*N/A - Not Available

Table B-6: Adhesion Results - Flexolith 216

Location	Failure by Type					Average Pounds Pull	Average psi	Overlay Thickness	Age at time of test
	1	2	3	4	5				
WB Madison		3			1	1900	605	3/16 - 7/16 inch	15 months
WB Madison	1	1			2	1675	533	3/16 - 1/4 inch	15 months
WB Madison		2	1			2100	668	3/16 - 1/4 inch	15 months
EB Madison	4					769	245	1/4 - 5/16 inch	15 months
EB Madison	4					1194	380	1/4 - 5/16 inch	15 months
EB Madison	4					1281	408	5/16 inch	15 months
WB East Garrison	3			1		1031	328	1/4 inch	10 months
WB East Garrison	4					1013	322	3/16 - 1/4 inch	10 months
WB East Garrison	2	2				1100	350	5/32 - 7/32 inch	10 months
EB East Garrison	2			2		1088	346	1/4 inch	10 months
EB East Garrison	2	1		1		1167	372	3/16 inch	10 months
EB East Garrison	2	1		1		1156	368	3/16 inch	10 months

Table B-7: Adhesion Results - Degadur MMA

Location	Failures by Type					Average Pounds Pull	Average PSI	Overlay Depth	Age at the time of test
	1	2	3	4	5				
WB Fairmont	2				2	1125	358	3/8 inch	10 months
WB Fairmont		1			3	956	304	3/8 inch	10 months
WB Fairmont	3				1	700	223	3/8 inch	10 months
EB Fairmont	3				1	1225	390	3/16 - 1/4 inch	10 months
EB Fairmont	2	1			1	1044	332	3/16 - 1/4 inch	10 months
EB Fairmont	3			1		1369	436	3/16 - 1/4 inch	10 months

Table B-8: Silica Fume Quality Control Data (Galen)

Test Specimen	Direction	Slump (Inches)	Air Entrainment (Percent)	4-Day Compressive Strength* (psi)	14-Day Compressive Strength* (psi)	28-Day Compressive Strength* (psi)
Lot 1-Test 1	WB	5.5	4.5	5875	7284	8188
Lot 1-Test 2	WB	6.5	5.5	5564	7036	8015
Lot 2-Test 1	WB	6.5	6.5	3463	5594	6373
Lot 2-Test 2	EB	6.5	6.0	4668	6602	7522
Lot 3-Test 1	EB	8.0	6.0	4730	6641	7773
Lot 3-Test 2	EB	6.5	6.0	4794	6788	7451

*Single cylinder values

Table B-9: 1996 Skid Testing Results - 40 mph, Ribbed Tire

Location	Milepost	Material	Direction	Speed (mph)	Air Temp. (°F)	Surface Temp. (°F)	Skid Number	Material Average
E. Garrison	175.5	Flexolith	EB	41	70	81	55.2	
E. Garrison	175.5	Flexolith	EB	41	70	81	56.7	
E. Garrison	175.6	Flexolith	WB	40	70	81	58.7	
E. Garrison	176.5	Flexolith	WB	40	70	81	59.1	
Madison	278.7	Flexolith	EB	40	70	81	52.7	
Madison	278.8	Flexolith	EB	40	70	81	55.1	
Madison	278.9	Flexolith	WB	40	70	81	55.5	
Madison	278.9	Flexolith	WB	40	70	81	51.8	**55.6**
W. Garrison	174.3	Thorotop	EB	40	70	81	45.8	
W. Garrison	174.4	Thorotop	EB	40	70	81	44.1	
W. Garrison	174.4	Thorotop	WB	39	70	81	45.7	
W. Garrison	174.5	Thorotop	WB	39	82	98	40.5	
W. Garrison	174.6	Thorotop	WB	40	70	81	46.7	
Gallatin	292.4	Thorotop	EB	40	70	81	43.9	
Gallatin	292.5	Thorotop	WB	41	70	81	38.5	**43.6**
Fairmont	210.8	Degadur MMA	EB	40	70	81	43.1	
Fairmont	210.8	Degadur MMA	WB	40	70	81	37.4	
19th Street	305.1	Degadur MMA	EB	41	70	81	43.6	
19th Street	304.7	Degadur MMA	WB	39	70	81	41.5	**41.4**

Table B-10: Skid Testing Results - 40 mph, Smooth Tire

Location	Milepost	Material	Direction	Speed (mph)	Air Temp. (°F)	Surface Temp. (°F)	Skid Number	Material Average
W. Garrison	174.3	Thorotop	EB	42	81	97	26.5	
W. Garrison	174.4	Thorotop	EB	41	81	97	26.3	
W. Garrison	174.5	Thorotop	WB	40	83	105	32.7	
W. Garrison	174.6	Thorotop	WB	40	83	105	20.3	
Gallatin	292.4	Thorotop	EB	40	83	105	20.4	
Gallatin	292.5	Thorotop	WB	41	83	105	24.5	**25.1**
Fairmont	210.8	Degadur MMA	EB	40	81	97	27.0	
Fairmont	210.8	Degadur MMA	WB	39	83	105	26.7	
19th Street	306.0	Degadur MMA	EB	40	83	105	31.8	
19th Street	305.2	Degadur MMA	WB	39	83	105	26.6	**28.0**
E. Garrison	175.5	Flexolith	EB	41	81	97	47.8	
E. Garrison	175.6	Flexolith	EB	41	81	97	48.4	
E. Garrison	175.9	Flexolith	WB	40	83	105	56.4	
E. Garrison	176.0	Flexolith	WB	39	83	105	57.0	
Madison	278.8	Flexolith	EB	40	81	97	44.3	
Madison	278.8	Flexolith	EB	41	81	97	37.5	
Madison	278.9	Flexolith	WB	41	83	105	43.1	
Madison	279.0	Flexolith	WB	39	83	105	44.7	**47.4**

Table B-11: Skid Testing Results - 50 mph, Ribbed Tire

Location	Milepost	Material	Direction	Speed (mph)	Air Temp. (°F)	Surface Temp. (°F)	Skid Number	Material Average
W. Garrison	174.3	Thorotop	EB	50	84	104	42.8	
W. Garrison	174.5	Thorotop	WB	49	82	98	40.5	
Gallatin	292.4	Thorotop	EB	50	82	93	37.6	
Gallatin	292.5	Thorotop	WB	51	82	99	37.7	**39.6**
E. Garrison	175.6	Flexolith	EB	50	84	104	52.1	
E. Garrison	175.6	Flexolith	WB	50	82	98	56.0	
Madison	278.7	Flexolith	EB	50	82	98	50.9	
Madison	278.9	Flexolith	WB	50	82	98	58.4	**54.4**
Fairmont	210.8	Degadur MMA	EB	50	84	104	36.7	
Fairmont	210.9	Degadur MMA	WB	49	84	104	52.7	
19th Street	305.1	Degadur MMA	EB	50	70	81	47.3	**45.6**

Table B-12: Skid Testing Results - 50 mph, Smooth Tire

Location	Milepost	Material	Direction	Speed (mph)	Air Temp. (°F)	Surface Temp. (°F)	Skid Number	Material Average
W. Garrison	174.3	Thorotop	EB	50	84	97	28.9	
W. Garrison	174.5	Thorotop	WB	50	70	81	29.5	
Gallatin	292.4	Thorotop	EB	50	84	97	24.9	
Gallatin	292.5	Thorotop	WB	50	84	97	26.5	**27.5**
Madison	278.7	Flexolith	EB	50	84	97	37.8	
Madison	278.9	Flexolith	WB	50	84	97	42.8	
E. Garrison	175.6	Flexolith	WB	50	65	70	43.0	**41.2**
Fairmont	210.8	Degadur MMA	WB	50	65	70	27.7	
19th Street	305.8	Degadur MMA	EB	49	83	105	30.8	**29.2**

APPENDIX C

This appendix presents the results of some simple analyses performed on the adhesion and skid test results. These analyses include statistical comparisons of the adhesion properties and skid resistance of the various overlay treatments accompanied by graphs of these various test results.
The specific information presented consists of:

Analysis of Skid Tests: 40 mph, Ribbed Tire

Table C-1: 40 mph, Ribbed Tire Data

Thorotop	Flexolith	Degadur MMA
45.8	55.2	43.1
44.1	56.7	37.4
43.9	52.7	43.6
45.7	55.1	41.5
40.5	58.7	
46.7	59.1	
38.5	55.5	
	51.8	

Thorotop HCR vs. Flexolith 216

Unpaired t test
P value P<0.0001
Are means significantly different? (P < 0.05)
Yes
One- or two-tailed P value? Two-tailed
t, df t=8.759 df=10

How big is the difference?
Mean±SEM of Thorotop HCR
43.60±1.142 N=7
Mean±SEM of Flexolith 216
55.60±0.9097, N=8
Difference between means -14.20±1.621
95% confidence interval 10.59 to 17.81
R squared 0.8847

F test to compare variances
F,DFn, Dfd 1.195, 3, 7
P value 0.3789
Are variances significantly different? **No**

Thorotop HCR vs. Degadur MMA

Unpaired t test
P value 0.2652
Are means significantly different? (P < 0.05)
No
One- or two-tailed P value? Two-tailed
t, df t=1.188 df=9

How big is the difference?
Mean±SEM of Thorotop HCR 43.60±1.142
N=7
Mean±SEM of MMA 41.40±1.407 N=4
Difference between means -2.200±1.852
95% confidence interval -1.989 to 6.389
R squared 0.1356

F test to compare variances
F,DFn, Dfd 1.155, 6, 3
P value 0.4917
Are variances significantly different? **No**

Flexolith 216 vs. Degadur MMA

Unpaired t test
P value P<0.0001
Are means significantly different? (P < 0.05)
Yes
One- or two-tailed P value? Two-tailed
t, df t=8.312 df=13

How big is the difference?
Mean±SEM of Flexolith 216
55.60±0.9097 N=8
Mean±SEM of MMA 41.40±1.407 N=4
Difference between means 12.00±1.444
95% confidence interval -15.12 to -8.882
R squared 0.8416

F test to compare variances
F,DFn, Dfd 1.380, 6, 7
P value 0.3389
Are variances significantly different? **No**

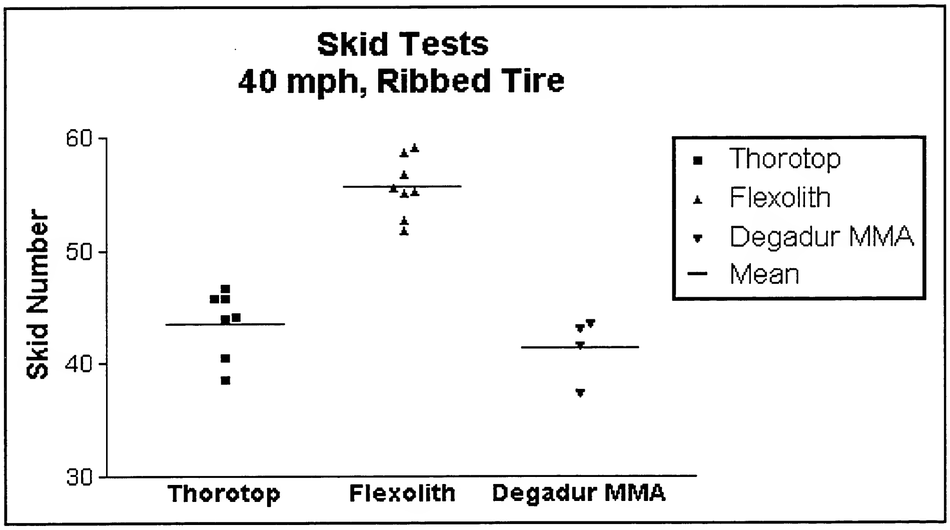


Figure C-1: 40 mph, Ribbed Tire Skid Tests

Analysis of Skid Tests: 40 mph, Smooth Tire

Table C-2: 40 mph, Smooth Tire Data

Thorotop	Flexolith	Degadur MMA
26.5	47.8	27.0
26.3	48.4	31.8
20.4	44.3	26.7
32.7	37.5	26.6
20.3	56.4	
24.5	57.0	
	43.1	
	44.7	

Thorotop HCR vs. Flexolith 216

Unpaired t test
P value P<0.0001
Are means significantly different? (P < 0.05)
Yes
One- or two-tailed P value? Two-tailed
t, df t=7.022 df=12

How big is the difference?
Mean±SEM of Thorotop HCR
25.12±1.885 N=6
Mean±SEM of Flexolith 216
47.40±2.344 N=8
Difference between means -22.28±3.174
95% confidence interval 15.37 to 29.20
R squared 0.8042

F test to compare variances
F,DFn, Dfd 2.061, 7, 5
P value 0.2216
Are variances significantly different? **No**

Thorotop HCR vs. Degadur MMA

Unpaired t test
P value 0.2886
Are means significantly different? (P < 0.05)
No
One- or two-tailed P value? Two-tailed
t, df t=1.136 df=8

How big is the difference?
Mean±SEM of Thorotop HCR
25.12±1.885 N=6
Mean±SEM of MMA 28.03±1.261 N=4
Difference between means -2.908±2.559
95% confidence interval -2.993 to 8.810
R squared 0.1390

F test to compare variances
F,DFn, Dfd 3.352, 5, 3
P value 0.1741
Are variances significantly different? **No**

Flexolith 216 vs. Degadur MMA

Unpaired t test
P value 0.0002
Are means significantly different? (P < 0.05)
Yes
One- or two-tailed P value? Two-tailed
t, df t=5.535 df=10

How big is the difference?
Mean±SEM of Flexolith 216
47.40±2.344 N=8
Mean±SEM of MMA 28.03±1.261 N=4
Difference between means 19.38±3.501
95% confidence interval -27.17 to -11.58
R squared 0.7539

F test to compare variances
F,DFn, Dfd 6.909, 7, 3
P value 0.0702
Are variances significantly different? **No**

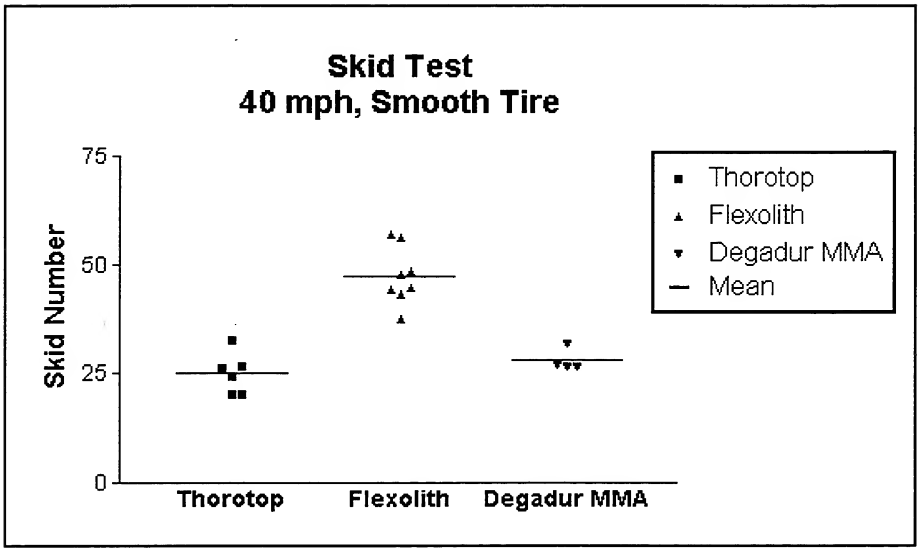


Figure C-2: 40 mph, Smooth Tire Skid Tests

Analysis of Skid Tests: 50 mph, Ribbed Tire

Table C-3: 50 mph, Ribbed Tire Data

Thorotop	Flexolith	Degadur MMA
42.8	52.1	36.7
37.6	50.9	47.3
40.5	56.0	52.7
37.7	58.4	

Thorotop HCR vs. Flexolith 216

Unpaired t test
P value 0.0005
Are means significantly different? (P < 0.05)
Yes
One- or two-tailed P value? Two-tailed
t, df t=6.883 df=6

How big is the difference?
Mean±SEM of Thorotop HCR
39.65±1.247 N=4
Mean±SEM of Flexolith 216
54.35±1.734 N=4
Difference between means -14.70±2.136
95% confidence interval 9.474 to 19.93
R squared 0.8876

F test to compare variances
F,DFn, Dfd 1.935, 3, 3
P value 0.3007
Are variances significantly different? **No**

Thorotop HCR vs. Degadur MMA

Unpaired t test
P value 0.2179
Are means significantly different? (P < 0.05)
No
One- or two-tailed P value? Two-tailed
t, df t=1.409 df=5

How big is the difference?
Mean±SEM of Thorotop HCR
39.65±1.247 N=4
Mean±SEM of MMA 45.57±4.699 N=3
Difference between means -5.917±4.199
95% confidence interval -4.880 to 16.71
R squared 0.2842

F test to compare variances
F,DFn, Dfd 10.66, 2, 3
P value 0.0433
Are variances significantly different?
Yes

Flexolith 216 vs. Degadur MMA

Unpaired t test
P value 0.1045
Are means significantly different? (P < 0.05)
No
One- or two-tailed P value? Two-tailed
t, df t=1.980 df=5

How big is the difference?
Mean±SEM of Flexolith 216
54.35±1.734 N=4
Mean±SEM of MMA 45.57±4.699 N=3
Difference between means 8.783±4.435
95% confidence interval -20.19 to 2.619
R squared 0.4396

F test to compare variances
F,DFn, Dfd 5.507, 2, 3
P value 0.0990
Are variances significantly different? **No**

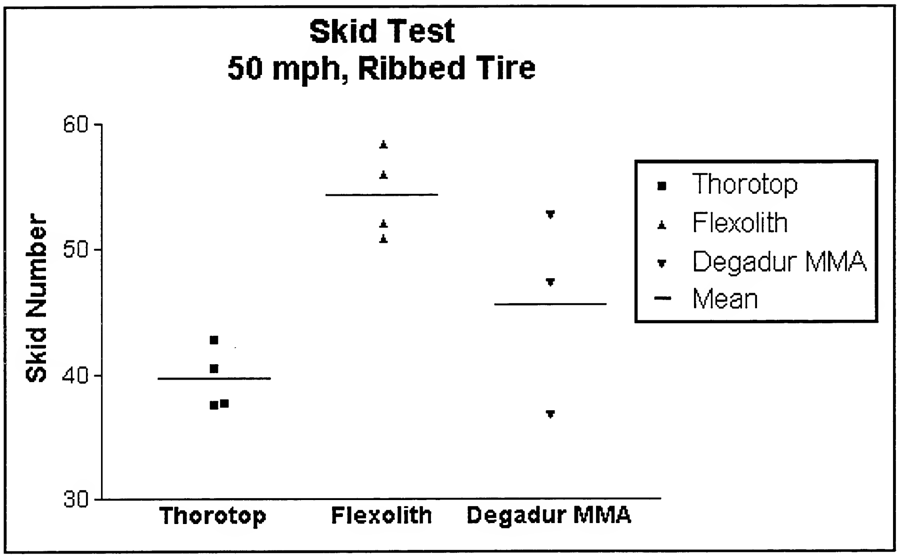


Figure C-3: 50 mph Ribbed Tire Skid Tests

Analysis of Skid Tests: 50 mph, Smooth Tire

Table C-4: 50 mph, Smooth Tire Data

Thorotop	Flexolith	Degadur MMA
28.9	37.8	30.8
24.9	43.0	27.7
29.5	42.8	
26.5		

Thorotop HCR vs. Flexolith 216

Unpaired t test
P value 0.0008
Are means significantly different? ($P < 0.05$)
Yes
One- or two-tailed P value? Two-tailed
t, df t=7.222 df=5

How big is the difference?
Mean±SEM of Thorotop HCR
27.45±1.069 N=4
Mean±SEM of Flexolith 216
41.20±1.701 N=3
Difference between means -13.75±1.904
95% confidence interval 8.855 to 18.64
R squared 0.9125

F test to compare variances
F,DFn, Dfd 1.899, 2, 3
P value 0.2931
Are variances significantly different? **No**

Thorotop HCR vs. Degadur MMA

Unpaired t test
P value 0.3887
Are means significantly different? ($P < 0.05$)
No
One- or two-tailed P value? Two-tailed
t, df t=0.9661 df=4

How big is the difference?
Mean±SEM of Thorotop HCR
27.45±1.069 N=4
Mean±SEM of MMA 29.25±1.550 N=2
Difference between means -1.800±1.863
95% confidence interval -3.372 to 6.972
R squared 0.1892

F test to compare variances
F,DFn, Dfd 1.051, 1, 3
P value 0.3806
Are variances significantly different? **No**

Flexolith 216 vs. Degadur MMA

Unpaired t test
P value 0.0171
Are means significantly different? ($P < 0.05$)
Yes
One- or two-tailed P value? Two-tailed
t, df t=4.816 df=3

How big is the difference?
Mean±SEM of Flexolith 216
41.20±1.701 N=3
Mean±SEM of MMA 29.25±1.550 N=2
Difference between means 11.95±2.481
95% confidence interval -19.85 to -4.054
R squared 0.8855

F test to compare variances
F,DFn, Dfd 1.806, 2, 1
P value 0.4656
Are variances significantly different? **No**

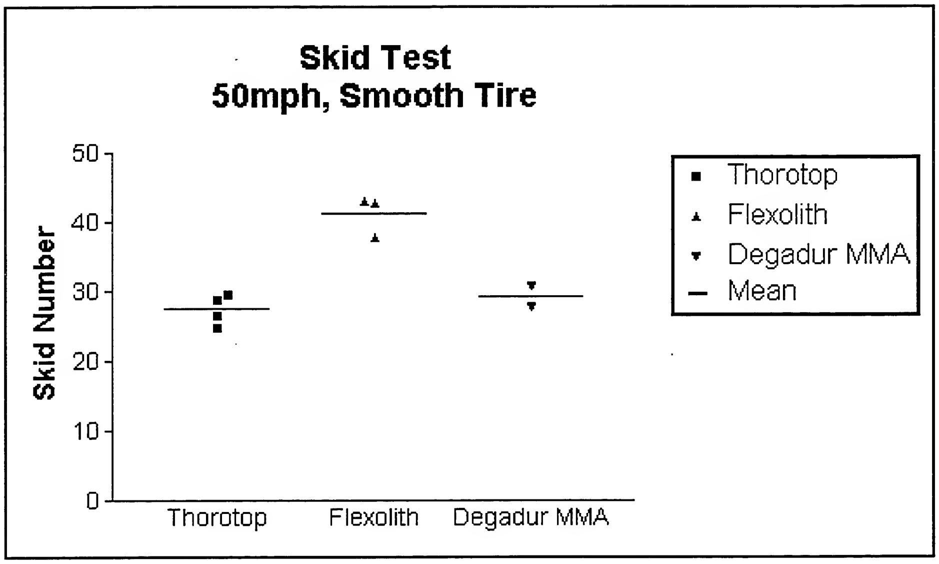


Figure C-4: 50 mph Smooth Tire Skid Tests

Table C-5: Adhesion Tests (psi)

Thorotop	Flexolith	Degadur MMA
48	151	175
119	183	191
119	247	191
127	255	279
127	271	279
143	279	286
143	279	286
143	279	310
159	287	318
159	287	318
167	326	326
175	326	334
175	326	342
191	334	350
191	342	350
199	342	374
215	342	390
223	358	414
223	358	446
231	374	454
247	382	462
255	382	533
263	382	541
271	390	
279	390	
286	398	
287	398	
287	406	
302	406	
318	414	
	422	
	446	
	446	
	446	
	454	
	501	
	525	
	565	
	573	
	597	
	676	
	692	
	708	
	804	

Analysis of Adhesion Tests

Thorotop HCR vs. Flexolith 216

Unpaired t test
P value P<0.0001
Are means significantly different? ($P < 0.05$)
Yes
One- or two-tailed P value? Two-tailed
t, df t=7.357 df=72

How big is the difference?
Mean±SEM of Thorotop HCR
202.4±12.31 N=30
Mean±SEM of Flexolith 216
403.4±20.90 N=44
Difference between means -201.0±27.32
95% confidence interval 146.5 to 255.5
R squared 0.4291

F test to compare variances
F,DFn, Dfd 4.227, 43, 29
P value P<0.0001
Are variances significantly different?
Yes

Thorotop HCR vs. Degadur MMA

Unpaired t test
P value P<0.0001
Are means significantly different? ($P < 0.05$)
Yes
One- or two-tailed P value? Two-tailed
t, df t=6.289 df=51

How big is the difference?
Mean±SEM of Thorotop HCR
202.4±12.31 N=30
Mean±SEM of MMA 345.6±20.49 N=23
Difference between means -143.2±22.77
95% confidence interval 97.45 to 189.0
R squared 0.4368

F test to compare variances
F,DFn, Dfd 2.122, 22, 29
P value 0.0292

Are variances significantly different?
Yes

Flexolith 216 vs. Degadur MMA

Unpaired t test
P value 0.0804
Are means significantly different? ($P < 0.05$)
No
One- or two-tailed P value? Two-tailed
t, df t=1.776 df=65

How big is the difference?
Mean±SEM of Flexolith 216 403.4±20.90 N=44
Mean±SEM of MMA 345.6±20.49 N=23
Difference between means 57.78±32.53
95% confidence interval -122.8 to 7.233
R squared 0.04628

F test to compare variances
F,DFn, Dfd 1.992, 43, 22
P value 0.0424
Are variances significantly different?
Yes

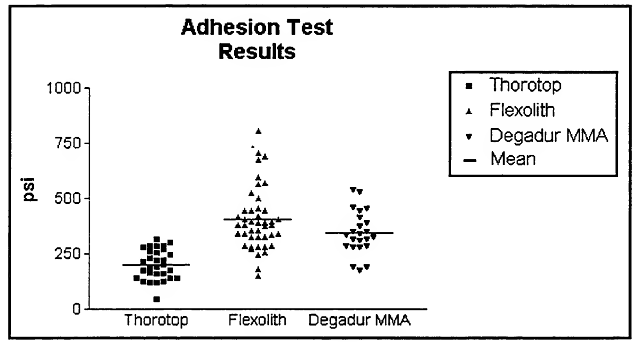


Figure C-5: Adhesion Tests